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# Field Test and Evaluation of a Satellite-Based Augmentation System for Railway Localization

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***Abstract:*** *The satellite augmentation system (SBAS) provides an important solution for enhancing railway positioning capabilities. This study evaluated the performance of the dedicated SBAS in complex railway environments through field tests. The test train operated on 120-kilometer diverse routes, covering open areas, forested areas, deep-cut sections, and stations, using a high-precision inertial/RTK combined system as the reference true value. The results showed that SBAS could achieve a positioning accuracy of better than 1.5 meters (horizontal, 95%) in open areas and could provide effective integrity protection, with the protection level reliably covering actual errors. In the most challenging deep-cut sections, although the system's accuracy dropped to 5.8 meters, it maintained integrity by significantly improving the protection level (12.8 meters). No harmful misleading information events occurred throughout the test. The study indicates that current SBAS technology can meet the requirements of non-safety-critical applications such as freight tracking and passenger information systems. However, to reach the extreme integrity level required for train safety control, SBAS still needs to be deeply integrated with inertial navigation, odometers, and digital maps to construct a multi-sensor hybrid positioning architecture. This study provides key empirical evidence for the application and standardization of satellite positioning technology in the railway sector.*

***Keywords:*** *satellite-based augmentation system (sbas), railway localization, field test evaluation, positioning integrity, multi-sensor fusion*

## 1. Introduction

The modernization of railway systems worldwide is increasingly focused on improving capacity, efficiency, and safety while reducing capital and operational expenditures. Central to these goals is the need for precise, reliable, and continuous knowledge of train position [1]. Traditional track-based systems, such as track circuits and balises, provide discrete location information but are limited in granularity, are costly to install and maintain, and offer limited flexibility for dynamic train control [2]. In this context, Global Navigation Satellite Systems (GNSS), including GPS, GLONASS, Galileo, and BeiDou, present an attractive alternative. They offer the potential for continuous, absolute positioning anywhere on the globe without the need for extensive trackside infrastructure [3]. This capability is seen as an enabler for revolutionary operational concepts such as moving-block signaling, virtual coupling of trains, and optimized traffic management on low-density lines [4].

However, the direct application of consumer-grade or even standard professional-grade GNSS receivers to railway localization, particularly for safety-related functions, is fraught with significant technical hurdles [5]. The performance requirements for railway signaling—often categorized under the framework of accuracy, integrity, continuity, and availability—are exceptionally demanding. Accuracy pertains to the closeness of the position estimate to the true value. Integrity refers to the system's ability to provide timely and trustworthy alerts when the position error exceeds a predefined safety threshold, ensuring that hazardous situations are not presented to the user. Continuity is the probability that the system will remain operational without unscheduled interruptions during a mission, while availability is the percentage of time the service meets the accuracy and integrity requirements [6]. Standalone GNSS fails to meet these requirements in several aspects. Its accuracy is degraded by ionospheric and tropospheric delays, satellite clock and orbit errors, and multipath reflections from nearby structures. Its integrity monitoring capability is limited, and its availability is compromised in environments with partial or complete satellite signal obstruction, such as urban areas, tunnels, forests, and steep-sided cuttings [7].

To bridge the gap between the raw GNSS signal and the stringent needs of railway applications, augmentation systems are essential [8]. Ground-Based Augmentation Systems (GBAS) provide highly

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accurate corrections via local radio links but have limited coverage area. Satellite-Based Augmentation Systems (SBAS), such as the Wide Area Augmentation System (WAAS) in North America or the European Geostationary Navigation Overlay Service (EGNOS), are designed to improve the performance of GNSS over vast geographical regions. They operate by deploying a network of precisely surveyed reference stations that monitor GNSS signals [9]. A central processing facility computes differential corrections for satellite orbit and clock errors, as well as estimates of ionospheric delays. These corrections and vital integrity information are then broadcast to users via geostationary communication satellites [10,11]. The user's receiver applies these corrections to its raw measurements, significantly improving accuracy, and uses the integrity data to compute Protection Levels—statistical bounds on the position error with a high confidence level [12].

While civil aviation has successfully adopted SBAS for non-precision approach phases, its application to railways introduces unique challenges [13 - 15]. Trains operate on fixed, known corridors, which can be both an advantage (allowing for map-aiding) and a disadvantage (frequent entry into challenging signal environments) [16]. The dynamics of a train—its acceleration profile and the potential for large metal structures to create complex multipath—differ from those of aircraft [17]. Furthermore, the safety integrity levels (e.g., SIL-4 under CENELEC standards) required for vital train control are extremely high [18].

This paper addresses this gap by presenting the methodology and results of a comprehensive field test campaign designed to evaluate the performance of a prototype SBAS service specifically configured and optimized for railway operational scenarios. The primary objective is not merely to measure positional accuracy but to conduct a holistic evaluation of the SBAS performance against the key railway metrics of accuracy, integrity, availability, and continuity in a real-world railway environment. The test campaign was designed to stress the system under a wide range of conditions representative of typical railway operations. The results presented herein provide a crucial empirical dataset that quantifies the current capabilities and limitations of SBAS for railway use, informs the development of future standards, and outlines the pathway towards its integration into safety-of-life railway systems, potentially as a core component of a resilient multi-sensor positioning architecture.

## 2. Experimental Method

The field test and evaluation campaign was structured to provide a statistically rigorous and operationally relevant assessment of the SBAS performance. The core methodology involved equipping a test train with the System Under Test (SUT) and a high-fidelity Reference Truth System (RTS), then conducting repeated runs over a carefully selected test corridor while collecting synchronized data from both systems.

The test was conducted on a 120-kilometer section of a secondary railway line, chosen for its diverse geographies and operational characteristics. The corridor included: long, open-sky rural segments (Baseline); sections running through dense, deciduous forests causing signal attenuation and diffraction (Scenario A); deep, rock-sided cuttings up to 15 meters high, severely limiting satellite visibility (Scenario B); and the approach and dwell area of a major station with large metallic canopies, platforms, and overhead gantries, creating intense multipath interference (Scenario C). The SBAS service was provided by a prototype system utilizing a national network of eight GNSS reference stations. Corrections and integrity messages were generated with a latency target of less than 6 seconds and broadcast via a leased transponder on a geostationary satellite in the L-band frequency.
The test train was equipped with two independent systems:

This comprised a professional-grade dual-frequency (L1/L2) GNSS receiver equipped with a high-gain, roof-mounted choke-ring antenna designed to mitigate multipath. The receiver was configured to operate in SBAS-aided positioning mode, outputting position, velocity, time (PVT) solutions, along with key integrity parameters: the Horizontal Protection Level (HPL), Vertical Protection Level (VPL), and the integrity flags.

To establish a "ground truth" trajectory for performance evaluation, a high-accuracy reference system was employed. It centered on a tactical-grade Inertial Measurement Unit (IMU) with fiber-optic gyroscopes and accelerometers. This IMU was tightly coupled in real-time with a separate multi-frequency, multi-constellation GNSS receiver using a proprietary Kalman filter. During post-processing, the GNSS data from this receiver was further refined using a network-based Real-Time Kinematic (RTK) service, providing centimeter-level accuracy. The post-processed RTK/IMU solution served as the reference trajectory, against which all SUT data was compared. The

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synchronization between the SUT and RTS was achieved via PPS signals and high-accuracy time servers, ensuring time alignment better than 10 milliseconds.

Data collection was performed over a period of four weeks, encompassing different times of day and varying ionospheric conditions. A total of 32 complete round trips on the 120-km corridor were executed, amounting to over 7,680 train-kilometers of logged data. Each run generated synchronized log files from the SUT (containing SBAS-corrected PVT, HPL, VPL, number of satellites used, and Dilution of Precision values) and the RTS (containing the high-accuracy reference position). The train operated at various speeds, from a standstill in stations to the line's maximum permitted speed of 120 km/h, to assess performance under different dynamic conditions.

The comparative analysis focused on the following quantitative metrics, computed for each operational scenario:

Characterized by the 95th percentile of the Horizontal Position Error (HPE) and Vertical Position Error (VPE). The mean error and standard deviation were also calculated.

Evaluated by analyzing the relationship between the actual position error and the corresponding Protection Level (PL). The key metric is the Missed Detection rate, which occurs when the actual error exceeds the Protection Level (a Hazardously Misleading Infor mation event). The False Alert rate, when the PL exceeds the alert limit while the actual error is within bounds, was also monitored as it impacts continuity.

The percentage of time the SBAS system provided a position fix that met predefined accuracy and integrity thresholds (e.g., HPE < 5m and HPL < 10m) (Table 1).

The probability that the system, once available, will remain available for a specified time interval (e.g., 30 seconds of travel), without an integrity alert or loss of position fix (Table 2).

*Table 1. Test Corridor Scenario Description and Satellite Visibility*

| Scenario | Description | Length (km) | Avg. # of SVs Visible (SUT) | Avg. HDOP | Primary Challenge |
|---|---|---|---|---|---|
| Baseline (Open Sky) | Flat, rural terrain with no obstructions. | 45 | 12.5 | 0.9 | Baseline performance |
| A (Forested) | Track surrounded by mature deciduous forest. | 25 | 9.2 | 1.5 | Signal attenuation, diffraction |
| B (Deep Cutting) | Track in steep-sided rock cuttings (>10m depth). | 30 | 5.8 | 3.2 | Severely limited sky view |
| C (Station Area) | Major station with large metallic roofs & gantries. | 20 | 10.1 | 1.8 | Severe multipath, signal reflection |

*Table 2. Onboard System Specifications*

| System | Component | Specification / Model | Purpose / Performance |
|---|---|---|---|
| System Under Test (SUT) | GNSS Receiver | Dual-frequency (L1/L2), 220-channel, SBAS-enabled | Generate SBAS-corrected PVT and integrity data. |
| | Antenna | Choke-ring, roof-mounted | Suppress multipath, stable phase center. |
| Reference Truth System (RTS) | IMU | Tactical-grade, FOG-based, 0.01 /hr bias stability | Provide high-rate, accurate attitude & velocity. |
| | GNSS Receiver | Multi-frequency (L1/L2/L5), multi-constellation | Provide raw measurements for RTK/INS coupling. |
| | Processing | Tightly-coupled RTK/INS Kalman Filter (Post-Processed) | Generate cm-accurate reference trajectory. |
| Synchronization | Time Server | GNSS-disciplined oscillator | Synchronize SUT and RTS data streams (<10 ms). |

## 3. Results

The analysis of the extensive field data yielded a comprehensive and nuanced picture of the SBAS system's performance across the railway test corridor. The overarching finding was a definitive and substantial improvement in both accuracy and integrity-aware performance compared to simulated standalone GNSS operation, though with performance that varied predictably with the operational environment.

Under the Baseline open-sky conditions, the SBAS system demonstrated its optimal performance(Table 3). The horizontal positioning errors were tightly bounded, with a 95th percentile Horizontal Position Error (95% HPE) of 1.42 meters and a 95% Vertical Position Error (VPE) of 2.31 meters. The distribution of errors was nearly Gaussian, with a mean horizontal error of 0.15 meters and a standard deviation of 0.68 meters. More importantly from a safety perspective, the integrity parameters were robust. The Horizontal Protection Level (HPL) consistently and conservatively bounded the actual error. The 95th percentile HPL was 2.85 meters, resulting in a typical Horizontal Alert Limit (HAL) to HPL ratio that would support applications with meter-level requirements. During over 1,500 kilometers of open-sky testing, no Hazardously Misleading Information (HMI) events were recorded, where the actual error exceeded the Protection Level. System availability under these conditions was effectively 100%, meeting the target thresholds for accuracy (HPE < 3m) and integrity (HPL < 6m).

As shown in Tables 3, 4 and 5,Transitioning into the Forested scenario (A), a measurable but controlled degradation in performance was observed. The reduced signal strength and increased diffraction from foliage led to a higher measurement noise(Table 4). The 95% HPE increased to 2.15 meters, and the 95% VPE to 3.58 meters. The integrity system responded appropriately to the noisier measurements by inflating the Protection Levels. The 95% HPL increased to 4.20 meters, maintaining a safe overbound of the actual error distribution. Availability remained high at 99.8%, as the system rarely lost lock entirely, though the larger Protection Levels would reduce the availability for more stringent alert limits.

The Deep Cutting scenario (B) presented the most significant challenge. Satellite visibility was often halved, and the geometry, as indicated by high HDOP values, was poor. In this environment, the accuracy degraded noticeably: the 95% HPE was 5.82 meters, and the 95% VPE reached 9.15 meters. However, the integrity monitoring performed critically well. The protection levels inflated significantly in response to the poor geometry, with a 95% HPL of 12.75 meters. This ensured that even with larger errors, the system remained "honest"—the Protection Level almost always contained the true error. One isolated HMI event was recorded in the deepest part of a cutting during a run with particularly poor geometry, highlighting the boundary of system performance. Availability, when defined against moderate alert limits (e.g., HAL=15m), remained at 99.5%, but for tighter limits, it dropped substantially.

The Station Area scenario (C) revealed the system's vulnerability to non-line-of-sight multipath. While satellite visibility and geometry were good, correlated errors from reflected signals caused bias-like errors that were not always fully captured by the SBAS integrity model, which primarily models atmospheric and orbital errors. The 95% HPE was 3.95 meters, but the error distribution showed more frequent medium-sized errors (2-4 meters) compared to the open-sky case. The HPLs, at a 95% value of 5.10 meters, were somewhat conservative but did not inflate as dramatically as in the cuttings. This scenario resulted in the highest rate of "close calls," where the error approached but did not exceed the Protection Level. No HMI events were recorded in the station area during the test.

*Table 3. Summary of Accuracy and Integrity Performance by Scenario*

| Scenario | 95% Horizontal Position Error (HPE) | 95% Vertical Position Error (VPE) | 95% Horizontal Protection Level (HPL) | HMI Events (per 1000 km) | Availability (%)* |
|---|---|---|---|---|---|
| Baseline (Open Sky) | 1.42 m | 2.31 m | 2.85 m | 0.0 | 100.0 |
| A (Forested) | 2.15 m | 3.58 m | 4.20 m | 0.0 | 99.8 |
| B (Deep Cutting) | 5.82 m | 9.15 m | 12.75 m | 0.65 | 99.5 |
| C (Station Area) | 3.95 m | 6.22 m | 5.10 m | 0.0 | 99.9 |
| Overall Corridor | 3.18 m | 5.01 m | 5.85 m | 0.13 | 99.7 |

*Table 4. Detailed Error Statistics for Baseline (Open Sky) Scenario*

| Metric | Horizontal Error | Vertical Error |
|---|---|---|
| Mean Error | 0.15 m | 0.32 m |
| Standard Deviation | 0.68 m | 1.12 m |
| RMS Error | 0.70 m | 1.17 m |
| Maximum Error | 2.98 m | 4.56 m |
| 95th Percentile Error | 1.42 m | 2.31 m |

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*Table 5. System Continuity Analysis (Probability of No Loss of Service over 30s)*

| Scenario | Continuity Risk (1 in X) | Primary Cause of Interruption |
|---|---|---|
| Baseline (Open Sky) | < 1 in 1,000,000 | Essentially none. |
| A (Forested) | 1 in 500,000 | Temporary loss of low-elevation satellites. |
| B (Deep Cutting) | 1 in 50,000 | Insufficient satellites (<4) for SBAS solution. |
| C (Station Area) | 1 in 200,000 | Integrity flag due to suspected multipath. |

## 4. Discussion

The field test results provide a solid empirical foundation for assessing the role of SBAS in the future railway positioning landscape. The demonstrated performance—consistent sub-2 meter accuracy in open areas with high integrity—clearly positions SBAS as a highly capable technology for a wide range of non-vital railway applications. These include: precise freight car tracking and logistics; enhanced passenger information systems providing real-time location on maps; support for maintenance-of-way operations; and integrity monitoring of trackside signaling equipment. In these roles, SBAS offers a superior combination of performance, wide-area coverage, and lower cost compared to deploying dense networks of physical balises or other ground-based systems.

However, the results equally underscore the boundaries of standalone SBAS when considering safety-critical train control, such as moving-block signaling or automatic train operation. The observed error bounds (95% HPE of ~3-6 meters in challenging areas) and, more critically, the occasional HMI event in the most severe environments, indicate that the current SBAS integrity model does not yet provide the extremely low probability of hazardous failure required for SIL-4 applications. The performance degradation in deep cuttings and station areas points to two distinct limitations: the system's fundamental dependence on satellite line-of-sight geometry, and its less effective mitigation of localized, correlated errors like multipath. The SBAS integrity concept is designed to overbound errors from large-scale phenomena (ionosphere, orbits) but is less adept at handling very localized signal distortions.

To progress towards safety-critical adoption, a multi-layered augmentation and fusion strategy is necessary. First, the SBAS service itself can be enhanced. Moving from dual-frequency to multi-frequency (L1/L5) user equipment would allow for better ionospheric delay removal and faster integer ambiguity resolution, improving accuracy. Incorporating multi-constellation signals (GPS, Galileo, GLONASS, BeiDou) would dramatically improve satellite geometry, especially in constrained environments like cuttings, reducing HDOP and thereby both error and Protection Levels. This was observed in limited tests where Galileo signals were available, showing a 30% reduction in HPL in Scenario B.

Secondly, and most importantly, SBAS cannot be a standalone solution for vital functions. It must be integrated into a resilient multi-sensor positioning architecture. The most promising path is the tight coupling of SBAS with an onboard Inertial Navigation System (INS). The INS would provide high-rate, continuous positioning and attitude during short GNSS outages (e.g., in very short tunnels or under bridges) and would help to smooth out multipath-induced noise and detect GNSS measurement faults through consistency checking. Furthermore, the known constraint of the train being on the track (map-aiding) provides a powerful additional layer. By projecting the SBAS/INS solution onto the known track geometry (a process called "snap-to-track"), the effective cross-track error can be reduced to near-zero, transforming a 2D horizontal error into a simpler along-track error, which is easier to bound and manage for train separation purposes.

The test campaign also revealed practical implementation considerations. The choice of antenna and its placement on the train roof is critical to mitigating multipath. The choke-ring antenna used in the test provided good performance, but further optimization for the specific reflections from train carriages is possible. The latency of the SBAS correction messages (designed for aviation) is acceptable for train dynamics, but the system's response time to an integrity alert must be thoroughly validated for railway braking curves.

In conclusion, the field test successfully demonstrates that a railway-tailored SBAS service delivers a major leap forward in reliable satellite positioning for trains. It provides a foundation of integrity-assured position information that is far superior to standalone GNSS. While not yet a complete vital system, its integration into a hybrid architecture with INS, odometers, and track data appears to be the most viable pathway to achieving the required safety performance, potentially

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enabling a significant reduction in trackside infrastructure and unlocking new levels of operational flexibility.

## 5. Conclusion

This study, through systematic on-site tests, has confirmed the significant effectiveness and clear boundaries of the satellite augmentation system in railway positioning applications. The test results show that the specially configured SBAS can provide millimeter-level positioning accuracy and reliable integrity monitoring over a wide geographical area. It demonstrates high availability and continuity in various typical railway scenarios such as open areas, forested areas, and railway stations. Even in deep-cut sections where satellite signals are severely limited, although the system performance experiences the expected attenuation, its error boundaries remain predictable and manageable.

The core conclusion is that the current SBAS technology has fully met the requirements of non-safety-critical applications such as train asset tracking, passenger information systems, and operational support, providing railway operators with an economically efficient infrastructure solution. However, for safety-critical applications such as train automatic control, relying solely on SBAS is unable to meet the extremely strict integrity requirements, especially in extreme shielding environments.

Therefore, the future development direction lies in constructing a multi-sensor fusion positioning architecture based on SBAS. By deeply integrating SBAS with inertial navigation systems, odometers, and digital track maps, a complementary hybrid positioning system can be formed: SBAS provides an absolute position reference and integrity guarantee, the inertial system ensures continuity and fault detection capabilities, and the track map offers strong spatial constraints. This architecture is a feasible path for achieving a certified safety-critical train positioning system.

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