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Systematic Review

Implementation of Global Navigation Satellite Systems in Railway Traffic Control Systems: Overview of Navigation Systems, Application Areas, and Implementation Plans

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Abstract: This article characterizes and presents Global Navigation Satellite Systems in relation to rail transportation applications. Due to the review character of this article, a synthesis of the literature discussing issues related to the possibility of implementing satellite positioning systems in the framework of their use in the management and control of railway traffic was made. On the basis of the literature review, the area of potential implementation of Global Navigation Satellite Systems was identified, as well as assumptions regarding the architecture of such systems being defined, along with the definition of criteria for assessing the impact of the use of satellite systems on rail traffic safety. The purpose of the above is to direct the development of rail guidance and control systems to systems that enable precise localization of rail vehicles, thereby optimizing the use of rail infrastructure through the implementation of efficient and cost-effective localization systems. This article goes on to characterize existing Global Navigation Satellite Systems and future directions related to the use of new satellite constellations. The basis of this review is the last twenty years of scientific publications on the subject of research issues related to the use of satellite positioning in railway systems. Based on the review of the state of the art and the results of the analysis, it was determined that the most frequently mentioned area of use of satellite positioning systems is the European Train Control System, the functionality of which enables the implementation of the transportation process based on so-called moving block spacing. The results of this review of the current state of knowledge will direct those responsible for the development and implementation of modern systems in the direction and control of railway traffic.

Keywords: GNSS; ETCS; positioning; rail transportation; signaling; architecture; safety criteria; applications

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1. Introduction

Civilian geopositioning systems are experiencing explosive growth. A recent analysis of the Global Navigation Satellite System (GNSS) market shows two main application areas accounting for the majority of the market, which are intelligent transportation systems (ITSs) and location-based services. The modernization of U.S. Global Positioning Systems (GPSs) [1,2], Russia's GLONASS (Globalnaya Navigatsionnaya Sputnikovaya Sistiema) [3] and the development of Europe's Galileo [4,5], China's BeiDou [6,7], as well as Japan's QZSS (Quasi-Zenith Satellite System) [8,9] are progressing at a rapid pace, introducing expanded capability potential and higher performance levels for satellite positioning. The above is leading to new developments in system architecture, providing an opportunity for the development of new positioning strategies. Currently, GNSS is considered the best system for providing the ability to determine precise position globally, along with the ability to determine the speed and time of a localized object [10].

Detecting the current location of rail vehicles on the rail infrastructure network determines the safety, efficiency, and reliability of rail transportation. In addition, it indirectly affects safety at rail-road crossings, i.e., road safety, as well. In terms of the efficiency and reliability of transportation systems, the ability to detect a moving vehicle can improve the effective capacity of railway lines. As with technical diagnostics, effective identification of the current state of the transportation network determines the efficiency of the transportation system. The development of railways, with particular emphasis on high-speed railways, necessitates the modernization and improvement of traffic control equipment and systems. A special area of development, ensuring the safe and efficient use of rail transport, is the detection and localization of rail vehicles moving on the rail infrastructure [11,12]. The ability to accurately determine the position of a rail vehicle with a high degree of accuracy is a key element in the reliable operation of rail transportation. Therefore, in the field of rail vehicle detection and localization equipment and systems, there is a lot of research and analysis aimed at developing existing or creating new solutions dedicated to rail vehicle positioning [13].

Mobility data based on GNSS tracking is widely used in many areas, such as travel pattern analysis [14], security research [15,16], transportation efficiency [1,17], and travel impact assessment. Within the transportation system, modes of transport are important mobility tools whose level of reliability is critical to the functioning of the flow of goods and movement of people [18]. This article aims to synthesize a review of the current state of the literature and practical solutions for identifying potential areas of application of GNSS in positioning, along with characterizing the available GNSSs, without making explicit recommendations on which system to use. In addition, this article focuses on identifying the basic characteristics and parameters that define functionality in the potential use of GNSS as part of a system responsible for positioning rail vehicles in railway infrastructure. In order to be able to implement satellite positioning systems for railway applications, knowledge of GNSS architecture is essential. Based on the available literature and applied technical and application solutions, it is necessary to define the general architecture of positioning systems, together with the definition of the relationship between satellite positioning and the logic of operation of the available railway guidance and control systems.

2. Methodology for Reviewing the Current State of Knowledge

The methodology of the state-of-the-art literature and state-of-the-art review implementation process includes a systematic approach to identifying the relevant GNSS positioning literature and areas of possible implementation. The process used for the literature review was based on the basic concepts of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) article flow [19]. The use of PRISMA can benefit many who are interested in the subject matter, as it allows for readers to assess the adequacy of the methods, and thus the reliability of the solutions, methods, and results of the projects and studies conducted. Presenting and summarizing the characteristics of the research contributing to the synthesis allows for the reader to assess the applicability of the results in the environment interested in the subject matter. Describing the solution in terms of evidence for the result and implementation can help stakeholders make appropriate recommendations for guidelines, instructions, and standards, in this case applied to rail transportation. Fully defining all elements of PRISMA also makes it easier to replicate and update the review, and to integrate systematic reviews into other reviews and guidelines, thus potentially optimizing research processes [20].

The number of articles collected from databases (Scopus, Web of Science, and Google Scholar) included a total of 1940 literature items. After removing duplicates, 1120 articles remained. According to the methodology presented below, the titles and abstracts of the articles were checked. Some articles were excluded from the process due to the following: the article did not focus on rail vehicle positioning; the full text was not available; the article did not cover GNSS. By performing the above process, the number of articles was reduced to 620. After a detailed review of the articles and an analysis of their applicability with regard primarily to the research problem, which for this review article is the identification of areas of possible application of GNSS in railway infrastructure, the number of articles was reduced to 94.

In addition, due to the continuous nature of changes and modernization of GNSS systems, and for the purpose of clarifying the current data on the satellite constellations of the various systems, an additional 2 literature items were included in this article, which are technical documents of positioning system managers. In addition, this article considers the most up-to-date book literature, which includes 4 items, 2 dissertations related to the issue discussed in this article, and 1 literature item from before 2000. The final number of all literature positions was 102. The process of verifying the literature resources is shown in Figure 1.

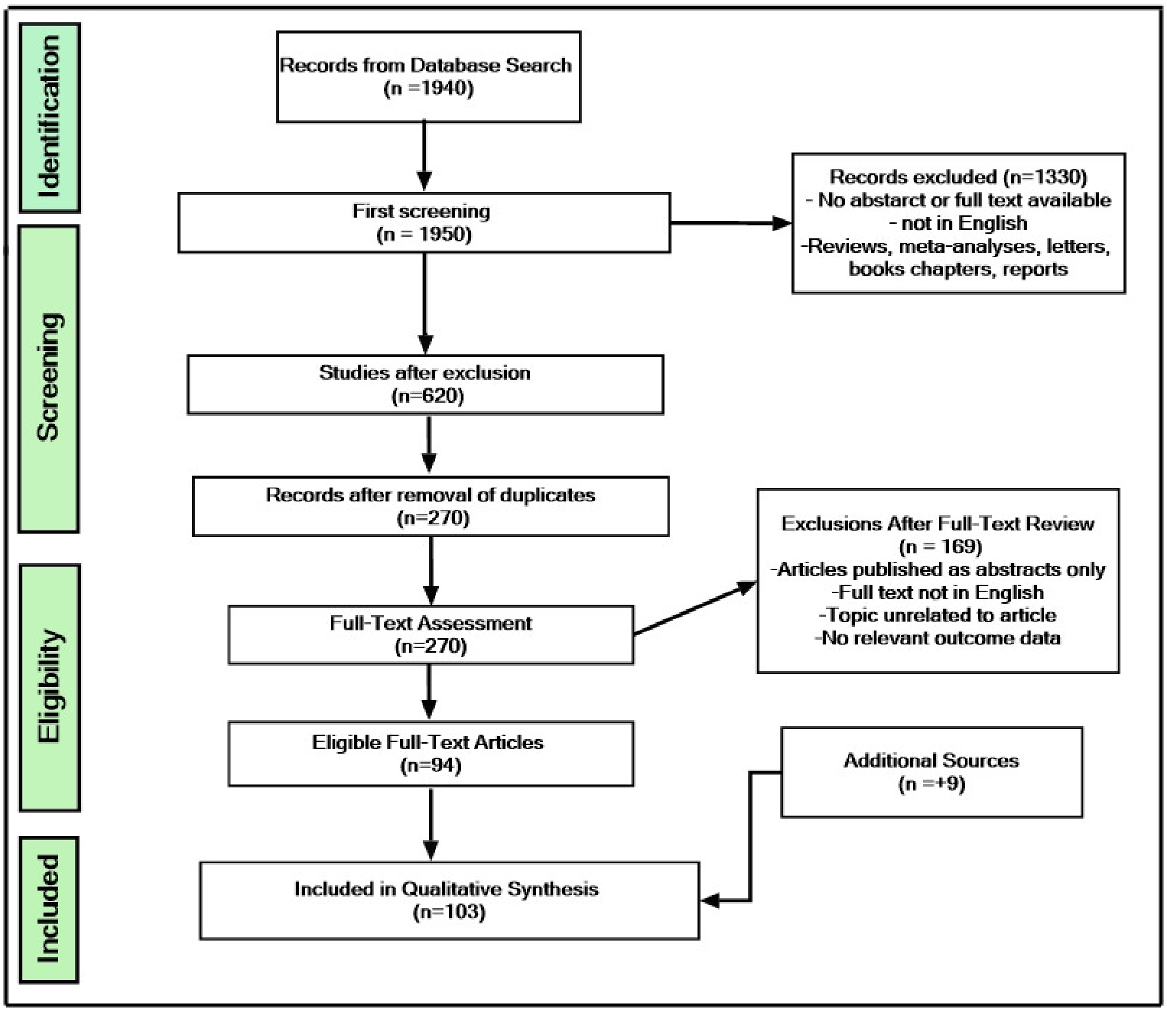

Figure 1. Diagram of the systematic review.

For this review article, the initial step was to formulate the research question and identify keywords and phrases related to the topic. A thorough literature search was then conducted using electronic databases. In the search for articles suitable for the current review, a number of keywords and phrases were used with the aim of reducing the list of electronic database items. Of the selected articles, a relevance check was performed based on their titles and abstracts. The full texts of relevant articles were then reviewed, and information and data were extracted, including those describing research, methods, results, and conclusions in the defined area of the literature review. The extracted data were synthesized and analyzed, and the results were organized and presented in the form of the current review article. The systematics of the review is shown in Figure 1, where the steps of the methodology used to synthesize publications related to the application of satellite systems in rail transportation are illustrated.

In accordance with the above, it was identified that the topics of the publication primarily focus on issues related to the definition of the architecture of the system based on localization of rail vehicles using GNSS. In this context, issues related to the architecture of multi-sensor systems, the use of digital maps in the implementation process of satellite systems, and the functioning and dependencies of GNSS segments were addressed. The above will clarify areas where the analysis of the feasibility of using satellite systems in rail transportation has some shortcomings for the implementation process. The GNSS implementation process itself in the literature review methodology will make it possible to identify a potential area for development and modification, adjusting technical and formal requirements. In addition, the literature review methodology takes into account the characteristics of individual satellite positioning systems due to the potential impact on rail traffic safety resulting from the use of specific systems or all systems available for positioning rail vehicles.

At the stage of initial selection of the state-of-the-art review, the number of citations of a given article and the IF (impact factor) index were used as one of the bibliometric indicators in determining the suitability of articles for this review. This review takes into account the literature items from the time interval between 2000 and the date of publication, and the trend of interest in issues related to the implementation of GNSS systems for rail vehicle positioning by three-year period is shown in Table 1 and Figure 2.

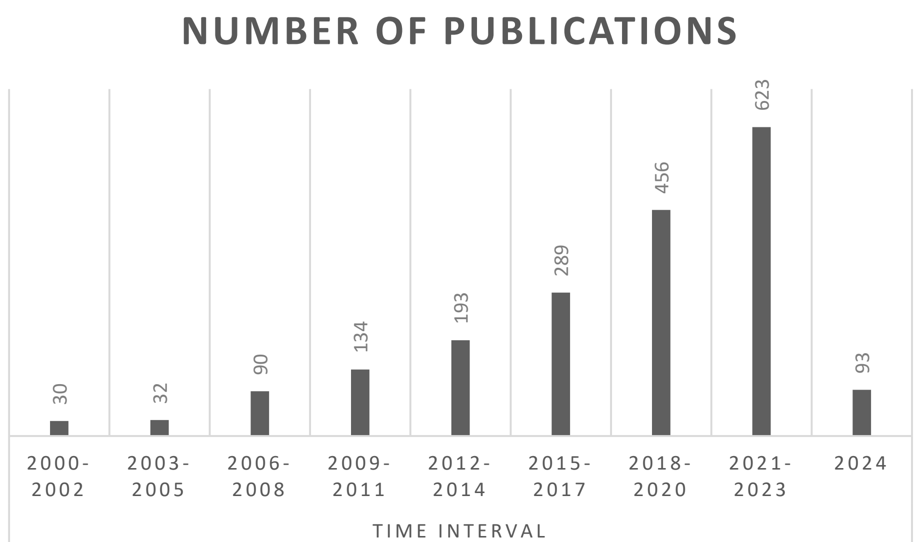

Figure 2. Chart of number of publications in three-year periods.

Table 1. Overview cross-section of literature items published since 2000 by three-year period.

	Time Interval								
	2000–2002	**2003–2005**	**2006–2008**	**2009–2011**	**2012–2014**	**2015–2017**	**2018–2020**	**2021–2023**	**2024**
Number of publications	30	32	90	134	193	289	456	623	93
Trend	-	2	58	44	59	96	167	167	-

According to the trend presented in Table 1, it can be observed that in the interval of the last two decades, the interest in the scientific community in the topic of GNSS implementation in railway infrastructure is gradually increasing. A significant increase is observed since 2015. The growth slows down in 2021–2023, which can be attributed to the constraints of the COVID-19 pandemic. By the publication deadline of 2024, the number of literature items shows a potency for an upward trend in terms of a three-year perspective.

Given the application of the PRISMA standard, the following steps in the literature review process were defined:

- Research question—"In what areas is it possible to apply Global Navigation Satellite Systems for rail vehicle positioning? How should the dependencies of satellite positioning systems be linked to rail traffic control systems?"
- Literature search—A systematic literature search was conducted using various online databases. The following terms were used in the above databases: "development of positioning systems", "GNSS", "satellite navigation", "rail vehicle positioning", "rail vehicle positioning systems", "railway safety criteria", and "implementation of satellite positioning systems". The choice of key words was based on the need to include separate issues for conventional approaches to rail vehicle detection and positioning, as well as future positioning solutions in the form of the use of satellite systems.
- Selection of articles—Articles were pre-screened based on their titles and abstracts, and then full-text analysis was carried out after selecting appropriate articles. The criteria for deciding whether to include an article in the reference list were whether the articles focus on GNSS issues in the area of railway applications with consideration of articles discussing case studies or practical applications and articles published in English. The following were used as exclusion criteria: articles unrelated to the research question. Data were then extracted and synthesized from selected articles, including information on satellite positioning system implementations, case studies, challenges, and future directions.
- Analysis and Interpretation—Data were analyzed and interpreted to identify common themes and patterns, as well as challenges and limitations of current projects and research.
- Writing and dissemination—The result of the conducted literature review was synthesized into a review article. This article was subject to review by competent reviewers to confirm its accuracy and complementarity, and then published.
- Registration—This systematic review was not registered in a publicly accessible database.

3. The Basic of GNSS

The performance and quality of modern train control systems depend mainly on the localization equipment and systems used. The main functions of such solutions are to determine the absolute position of the train, including the safety-appropriate confidence interval, speed, acceleration, and the assignment of trackside and mobile resources. The result of determining the location of a given rail vehicle is used for the needs of the traffic control and management system, on the basis of which railway traffic is carried out in a collision-preventing manner and optimized use of infrastructure, which has a significant impact on the safety and capacity of railway lines [21]. Fulfilment of the above criteria with regard to positioning functions can potentially be met through applications of GNSS functionality. The general assumptions for GNSS are that it is possible to extract GNSS position records and then use the data for analysis to determine the position of a rail vehicle on the rail infrastructure. The above is achieved by extracting features in the form of spatial and temporal information, such as, for example, speed, acceleration, direction, and distance for each vehicle individually or collectively for all in the localization area. The extracted features can serve as batch data for the rail traffic guidance and control systems to define a dynamic graph of rail traffic in the study area [18,22].

3.1. Reliability, Availability, Maintainability, Safety (RAMS), and Evaluation Criteria in Aeronautics

In the nomenclature and GNSS environment, system performance is defined by the criteria accuracy, availability, continuity, and reliability. These criteria, are based mainly on aeronautical applications and have been defined by the International Civil Aviation Organization (ICAO). They are not directly related to railway requirement criteria, usually qualified in terms of RAMS. A common evaluation criterion in aeronautical systems for RAMS analysis is the concept of reliability. The meaning of the above concept in relation to railway applications can be defined in terms of all possible failures, the probability of failure, and the impact of failure on the operation of the system. In both cases, reliability refers to the impact on the level of safety of the assessed application area. In addition, in comparing the ICAO evaluation criteria and the RAMS analysis, integrity is also a converging concept. For satellite navigation users, integrity is a quantitative measure characterizing confidence in the reported position. In railway transport, users speak of safety integrity to encompass a larger number of safety lifecycle requirements. The term integrity itself refers to the integrity of the train, that is, the fact that the train has not split and in the further implementation of positioning and unification systems may characterize such functions as diagnostics and reporting of rolling stock failures [23–26].

3.2. Terminology of Positioning Systems

The following defines the relevant technical positioning terms that are used to compare different satellite location systems in railway applications:

- Positioning—determining the specific location of a vehicle in relation to the rail network;
- Location system—configuration of technical components that provide location information;
- Spatial resolution—resolution represents the smallest increment of location information;
- Temporal resolution—represents the time lapse between two identical satellite raids over the same point.

3.3. Criteria for Technical Evaluation of GNSS Systems (Aeronautics)

The following technical evaluation criteria have been adopted for GNSS aeronautical applications:

- Positioning accuracy—There are two different requirements in terms of accuracy: accuracy along the track and accuracy transverse to the track. In both cases, safety-related localization systems for traffic control systems must provide as much accuracy as possible. The level of accuracy of rail vehicle positioning depends on the accuracy of equipment and systems, which determines that the functionality of a positioning system using satellite navigation will depend on the accuracy of those systems. For some non-safety applications, such as fleet monitoring, a high level of accuracy is not required. Such applications typically require a low accuracy of 50–300 m [21,27].
- Positioning availability (with respect to time)—The availability in question determines the probability that the system is available at the beginning of a specific object positioning task [21].

- Positioning availability (referring to space—coverage)—The term coverage describes the geographic area in which location information must be provided to the user/application [21,27].
- Integrity—The term integrity describes the requirement that the system must independently detect and report failures. It applies only to security-related systems [21].
- Continuity—The term continuity describes the ability of the system to perform the localization task it has started without any interference. Particularly when using GNSS, this problem arises when the vehicle passes through tunnels or covered stations, for example. These obstacles prevent or hinder the reception of satellite signals. For precise positioning, a measurement using at least four satellites is necessary, and the limitation due to obstacles can make a positioning system based on satellite localization unavailable. However, even in the situation of access to a sufficient number of satellites in a limited area, it causes the accuracy of horizontal positioning information to decrease at high altitude, because the distance between several satellites is too small for a precise measurement result. In such a case, the usefulness of the information may not be sufficient [21,27].
- Reliability—The term reliability refers to applications in safety-related systems. In safety-critical applications, knowing the position of a vehicle is very important. However, it is not only the position that is important, but also the confidence interval of the position information. Hidden errors in position information can lead to collisions and accidents. When deciding to use GNSS for positioning, it is important to consider the possibility of identifying errors in position information. The best way to do this is to use a combination of different systems to obtain position information [27]. The concept of reliability in the present context refers to solutions for using GNSS in aeronautics. At the same time, the term reliability appears in the RAMS (Reliability, Availability, Maintainability, Safety) criteria analysis, which is used in the evaluation of feasible solutions for railways. In view of the above, it is necessary to develop a consistent approach in the RAMS analysis of GNSS systems, which is discussed later in this article. A comparison of the relationship between RAMS and ICAO criteria is shown in Table 2.

3.4. Digital Map

An important part of the GNSS implementation process in railway applications is the digital map, which is a central and key element of safety-related positioning. Some navigation functions such as determining the distance travelled or actual speed can be performed without the use of a digital map. Others such as positioning cannot be performed without such a map, as it provides a complete description of the topological information of railway tracks and can be used as a reference to calibrate position estimation error and make the position result identified within a one-dimensional location coordinate defined on the track [28–30].

A database containing track maps enables train positioning, which, supported by various integration solutions at different levels of coupling, is considered a relatively low-cost and effective choice. The input data resulting from the information source, in the form of a digital map, supplements the satellite-based train positioning system with relevant information resulting from the map matching process, and should also be taken into account to evaluate and improve the integrity of positioning, which is important to ensure safety in satellite location-based systems in railway applications. As part of the studies included, in [31], high-integrity map matching algorithms for transportation applications were investigated and factors affecting the integrity of the map matching approach were analyzed, while [32] presented a solution based on multiple hypotheses to increase the correctness of identifying an occupied track section and achieve effective map matching. With the above in mind, it is important to be aware that the digital map is one of the elements generating possible positioning errors, as typical errors can arise at the stage of its creation. Even verification or validation may result in an insufficient level of security due to the risk of the above errors [33–35].

Table 2. Comparison of technical evaluation criteria.

Criteria	RAMS	ICAO
Security	Is defined as the probability of a device and system functioning in a safe state	
Continuity		Describes the ability of the system to perform the localization task it has started without any interference
Accuracy		The degree of correspondence between the estimated or measured value and the actual value
Availability	Determines the ability to maintain a functioning state in a given environment in which it can perform the required function, assuming that the required external resources are provided	With respect to time, determines the probability that the system is available at the beginning of a specific object positioning task; With respect to space (coverage), determines the geographic area in which location information must be provided to the user/application
Integrity	Integrity of the train, that is, the fact that the train has not split	Describes the requirement that the system must independently detect and report failures
Reliability	Determines the ability of the device and system to perform specific functions, at specific times and conditions	Refers to applications in security-related systems
Maintenance vulnerability	Determines the ability to perform timely and easy maintenance (including servicing, inspection and control, and repair and/or modification), assuming that the service is carried out in accordance with established procedures and measures	

3.5. System Architecture

The architecture of satellite navigation systems in the nomenclature used is divided into so-called segments, which include space segment, ground segment, and user segment. The above division defines the geographical structure of GNSSs; however, from the point of view of transmission of signals and information contained therein, GNSSs can be divided into space segment, ground segment, user terminal, and network auxiliary segment. The space segment transmits an authentication code along with authentication messages to the transmitted satellite navigation signal, the user segment authenticates the received satellite navigation signal, and the network auxiliary segment uses a communication base station (ground communication/satellite communication) to provide auxiliary network authentication information. If there is a GNSS spoofing signal in the real environment, the user segment can identify whether the current signal is a spoofing signal by authenticating the spread spectrum message/code. The architecture of satellite navigation signal authentication is shown in Figure 3 [36,37].

According to Figure 3, the architecture is dedicated to aeronautical applications, while satellite positioning systems for rail vehicles should use an architecture based on the integration of multiple sensors to avoid risks associated with potential GNSS errors, including unavailable or limited satellite signal, multi-path effects, and others. An example is inertial sensors, which appear to be a promising choice for most road transportation applications and also appear to be suitable for rail vehicles. The use of inertial sensors in the process of differential satellite positioning can provide an accuracy of about one meter, which can contribute to more efficient determination of train position, speed, and other required status descriptions. Within the framework of the global satellite navigation system scheme using inertial sensors (GNSS/INS) to supplement the odometer, the solution of the integrated satellite train positioning system architecture can be illustrated as shown in

Figure 4, where OBC stands for on-board computer and IMU is the inertial measurement unit. In order to support the GNSS-based train control system, the presented positioning system is designed with an interface for the on-board ATP (Automatic Train Protection) device [28,38–40].

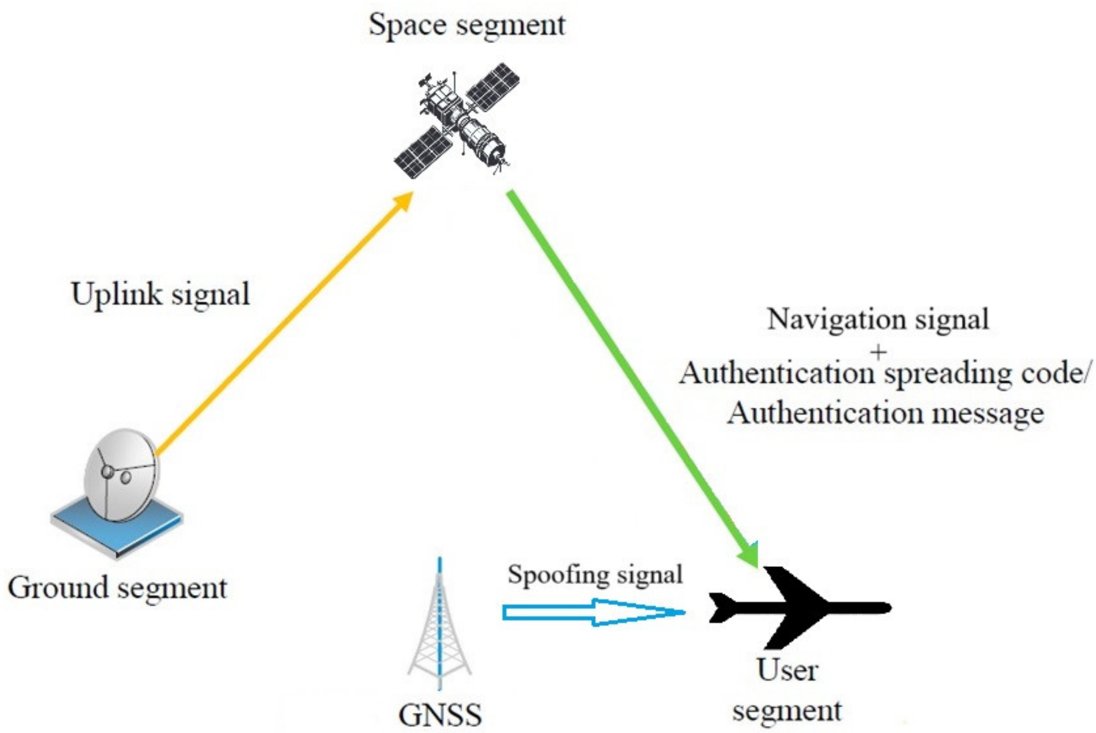

Figure 3. Satellite navigation system architecture with signal transmission. Prepared on the basis of [37].

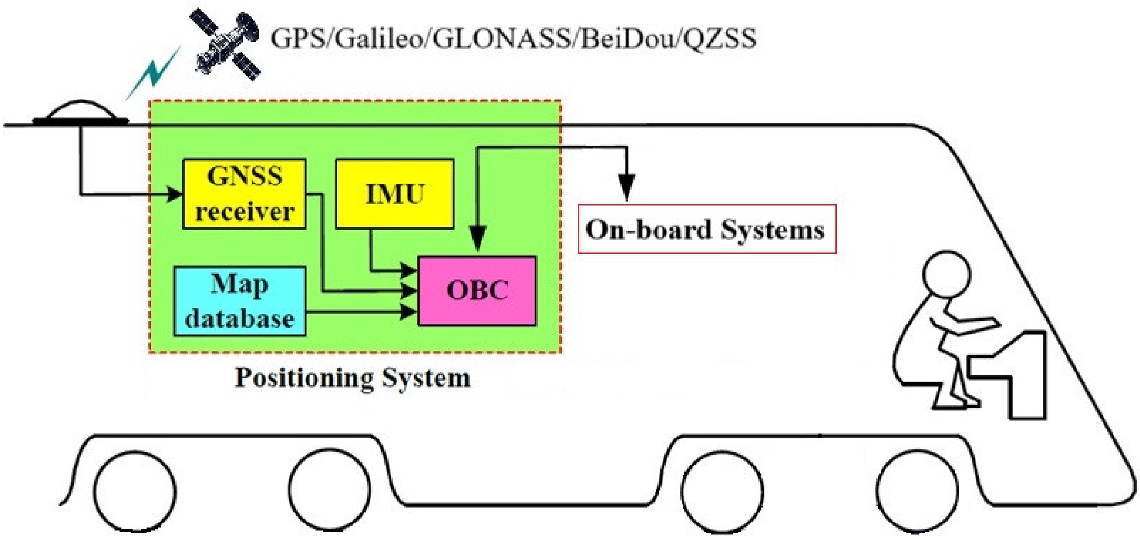

Figure 4. Example architecture of an on-board positioning system using a constellation of GPS/BDS satellites. Prepared on the basis of [28].

One multi-sensor solution, which collects data from various sensors installed in the vehicle (in particular, IMU and GPS) and performs Kalman-based filtering recursion, has been studied and presented in [41]. The study focused on solutions that could be applied to any rail vehicle, regardless of the ground equipment on specific lines. Another study [42] proposed an adaptive multi-sensor data fusion technique to accurately assess train position and speed based on three on-board sensors—a longitudinal accelerometer, an odometer, and a GPS receiver. An article [43] presents a rail vehicle localization technique based on the fusion of a tachometer and an IMU to improve performance in terms of speed and position estimation accuracy. This fusion was carried out through Kalman filtering theory. In another paper [44], a particle filter-based approach to localizing a rail-guided robot was presented. The filter was used to integrate odometry with inertial measurements, laser scans, and image data. As a result, a rail map, motion model, and perception model were developed to implement 1D estimation [45,46]. The synthesis of the architecture using multi-sensor systems is shown in Table 3.

Table 3. Characteristics of systems with multi-sensor architecture.

Multi-Sensor Architecture	Reference	Description
Kalman-based filtering recursion	[41]	Multi-sensor system that collects data from various sensors installed in the vehicle (in particular IMU and GPS) and performs Kalman-based filtering recursion
Adaptive multi-sensor data fusion technique	[42]	Precise evaluation of train position and speed based on three on-board sensors—longitudinal accelerometer, odometer, and GPS receiver
Fusion of tachometer and IMU	[44]	Improved performance in terms of accuracy of speed and position estimation by applying Kalman filtering theory
Particle filter	[45,46]	Integration of odometry with inertial measurements, laser scans, and image data, resulting in track maps, motion model, and perception model to implement 1D estimation

By correlating data from individual sensors, it is possible to obtain more comprehensive coverage regarding the location of a rail vehicle on rail infrastructure. According to the results of previous analysis and research, it is necessary to integrate the map with sensor data to provide information about the environment, such as the track on which the vehicle is traveling, the proximity to dangerous places, the tunnel, etc. In turn, the dynamic data detected by the sensor makes it possible to create a dynamic map with high precision. With the positioning sensor to obtain their position, combined with a precise map, it is easier to depict the traffic situation in the area covered by the system, in order to ensure the safety of railway traffic [47–49]. The use of multi-sensor solutions and dynamic digital maps requires a data transmission system with a wide bandwidth. A potential future solution is 5G transmission systems, whose high-bandwidth functionality will allow for rail vehicles equipped with multi-sensor systems to share more sensor data or combine them with precise maps for dynamic steering and control of railway traffic [50,51].

Over the past two decades, several projects have been carried out with research aimed at developing solutions to implement GNSSs in railway applications. The first major projects were APOLO [26,52], GADEROS [53], LOCOPROL [54], GaLoROI [25], and 3inSat [55]. The above projects were implemented in the first decade of the 2000s. All of these projects, even if they did not lead to the commercialization of operational products, certainly helped to introduce GNSS into the railway mentality. The next decade saw the launch of projects such as NGTC (Next-Generation Train Control) [56,57], which aimed to explore how new developments in ERTMS/ETCS for interoperable networks and CBTC (Communication-Based Train Control) systems for urban networks can be mutually leveraged. Satellite positioning is one of the goals of NGTC. Finally, the European Shift2Rail program [58–61], in its second innovative program (IP2) [62] on signaling, focuses specifically on reliable train positioning for advanced traffic management and control systems. The list of projects/programs is shown in Table 4.

Table 4. Projects/innovation programs in railways.

Project/Program	Time Range	System Architecture	References
APOLO	1998–2001	GPS receiver in various operating modes (standalone, DGPS, EGNOS) + odometer + gyroscope + accelerometer + Doppler radar	[26,52]
GADEROS	2001–2004	GPS + EGNOS + digital track map (a configuration with virtual balise database, hybridizing GNSS, an odometer, and a gyrometer)	[53]
LOCOPROL	2001–2004	GPS receiver + EGNOS + beacon + odometer	[54]
GaLoROI	2012–2014	Galileo receiver + eddy current sensors + map + redundant channels	[25]
3inSat	Completion 2016	Multi-constellation GNSS receiver + EGNOS + odometer + IMU	[55]
NGTC	During	NGTC is focusing on the application of satellite positioning functions within ERTMS/ETCS (virtual balise concept).	[56,57]
Shift2Rail—IP2	During	IP2 aims to develop a new generation of signaling and traffic control systems, based on the current ERTMS, to enable intelligent management of automated train traffic, optimize performance and reliability, and minimize operating costs.	[58–61]

A different architecture possible is to combine a GNSS receiver with capability signals and three-dimensional (3D) map matching techniques. An electronic track map is designed, generated, and stored as a static data source representing the railway lines of an area. As the most important part, track data are the basic elements that populate the database and describe practical rail lines at various scales. If GNSS signals fail, alternative signals such as Wi-Fi can be used to estimate the position of the train. The location of additional access points, such as in tunnels, will need to be determined to maintain position accuracy. Three-dimensional map matching will support position estimation in urban areas and can help determine the track on which the train is traveling. The map can also be used as a positioning aid and provide train heading information based on track location. This system has the advantage of being independent of the systems installed on the train. However, in accordance with the above-described risk regarding potential errors arising during the digital map stage, there may be a situation in which a positioning system based on the presented architecture fails to achieve the required level of reliability estimated under the RAMS criteria. Given the potential risks arising from the use of a digital map-based architecture, the use of an architecture whose topology would consist of a combination of the aforementioned GNSS/INS architecture and 3D map matching should be considered. The use of additional sensors, which are subject to certification in rail applications, could result in a significant increase in system reliability [63,64]. In the case of the development of the architecture described above, it should be borne in mind that it will be characterized by a complex topology of dependencies between the various elements of such an architecture. Increasing the number of devices, thus expanding the network of dependencies between each of them, may contribute to potential errors in the functioning of the system itself, and—as should also be borne in mind in the conception and design of such systems—will generate additional costs [65,66]. An example of the topology of the described architecture is shown in Figures 5 and 6.

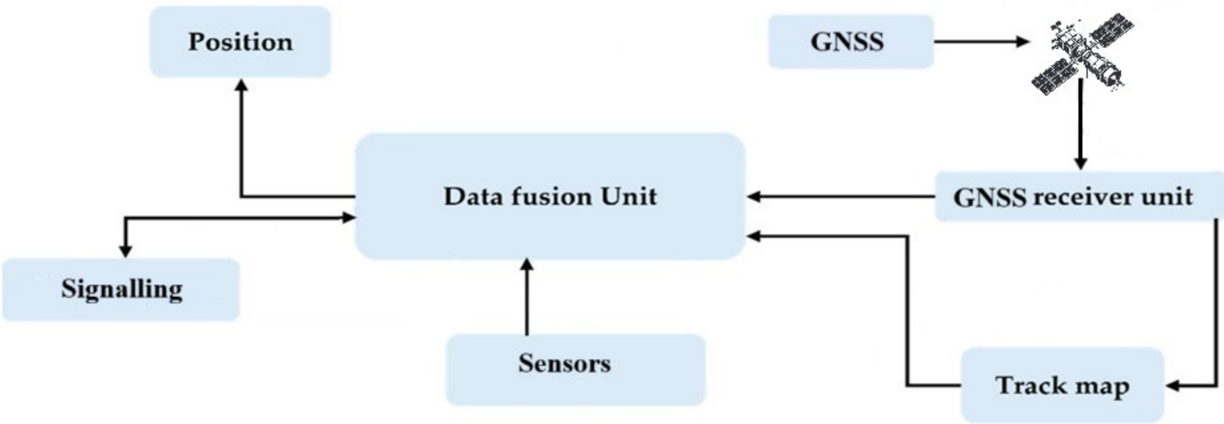

Figure 5. Basic architecture of a multi-sensor positioning system with GPS. Prepared on the basis of [46].

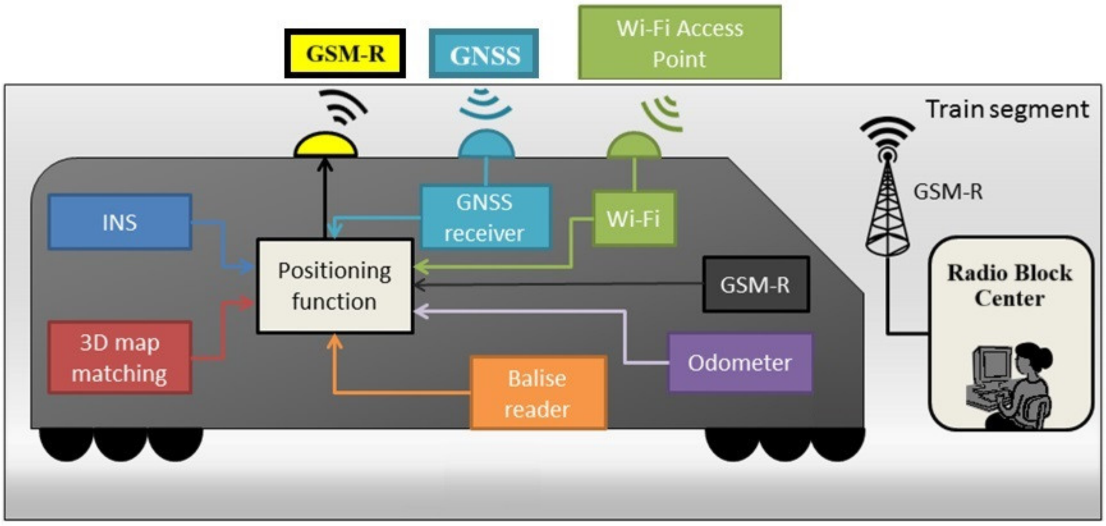

Figure 6. Physical architecture of a positioning system based on GNSS and Wi-Fi and GSM-R communications. Prepared on the basis of [63].

3.5.1. Space Segment

A constellation of multiple satellites, each with atomic clocks, is used to ensure that the system allows for users to continuously determine their position in all weather conditions anywhere on or near the Earth. The distance measurement method is based on measuring the difference in propagation delay of radio signals received from different satellites. The functionality of the system lies in the fact that, having signals received from precisely synchronized sources, the receiver does not need to be synchronized with the satellites as well, so no atomic clock is required for the receiver of the satellite signals. For two-dimensional positioning only, it is necessary to receive signals from at least three satellites, while at least four satellites are needed for three-dimensional positioning. It follows that to achieve global coverage, at least four satellites visible at all times from any point on Earth are required, which raises a significant design problem. The user on the ground cannot maintain strict synchronization with the satellites, and the ranges to different satellites calculated from observed delays are called pseudo-ranges. The true range must be calculated after accounting for clock error. In order to determine the receiver's location in three dimensions, latitude, longitude, and altitude, three true ranges are obviously required, hence the need for a fourth measured delay to calculate the receiver's clock error. If the clocks are synchronized and their assumed positions are correct, a single correction to the user's clock will cause all the spheres to intersect at a single point, the user's position.

The orbital parameters of the satellites are shown in Figure 7 and include the great orbital half-axis, orbital eccentricity, orbital inclination (the angle between the plane of the orbit and the plane of the Earth's equator), perigee argument (the angle between perigee and the node, the point where the plane of the orbit intersects the plane of the equator) and node elevation (an astronomical term for the azimuthal angle relative to the first point of Aries), and the epoch (time) of the perigee passage [67,68].

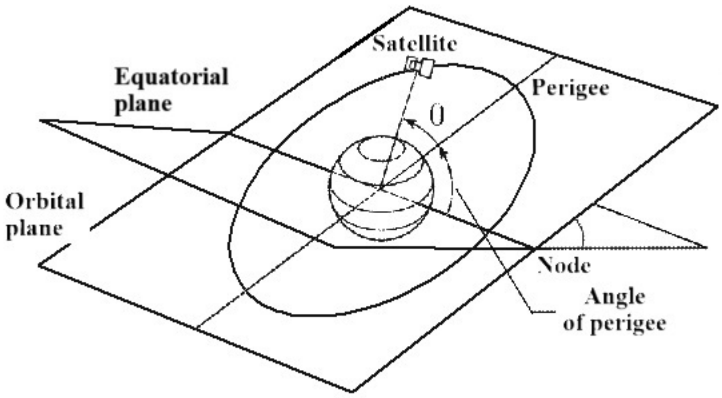

Figure 7. Orbital parameters of satellites. Prepared on the basis of [67].

3.5.2. Ground Segment

The ground component performs key functions to coordinate GNSS activities. These functions include tracking the many satellites that make up the GNSS constellation, monitoring their navigation transmissions to determine the status of their on-board subsystems, particularly their atomic clocks, and analyzing their ephemerides. The operational control component of the ground segment sends feedback commands and data to take corrective measures on the orbital parameters and on-board atomic clocks, and, if necessary, resolve any anomalies, ensuring that all subsystems operate according to specifications. These functions are performed by a global network of ground installations operated by the main control station. The main control station (MCS), otherwise known as the Mission Control Center, is the facility where the ground control team has sole responsibility for centrally controlling the operations of the entire system, 24 h a day. The ground control segment is supported by globally distributed monitoring stations in geodetically precise locations selected to ensure optimal coverage. The monitoring stations are equipped with atomic clocks with enhanced performance and GNSS receivers with geodetic-level measurement quality. The atomic clocks are characterized by high beam intensity. The time reference of the monitoring station at MCS is coordinated with the master clock. At all monitoring stations around the world, atomic clocks provide standard signals of equal frequency as references to their GNSS receivers. The main control station regularly receives satellite data from the monitoring stations regarding the satellites' ephemerides and atomic clock readings, as well as on-board systems data, information that is analyzed to determine firstly the status and integrity of the satellites' on-board systems, and secondly to determine their exact orbital positions and whether corrective action may need to be taken to ensure that all satellites are in constant transmission with the station. In the event of an emergency, such as a satellite failure, immediate action can be taken to reposition the satellite to maintain system integrity [67]. Figure 8 shows an example of ground segment architecture.

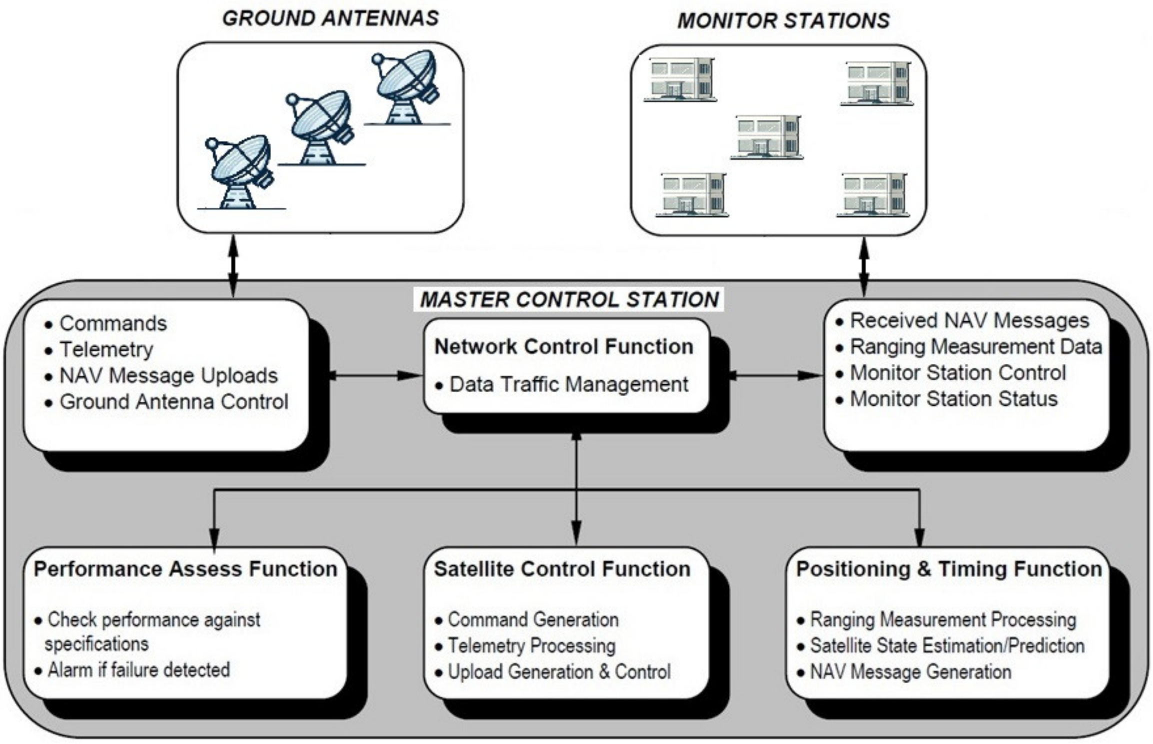

Figure 8. Ground (control) segment. Prepared on the basis of [69].

3.5.3. User Segment

The original premise for navigation systems such as GPS and GLONASS as global all-weather positioning systems was justified by military applications, but they were later opened up to the general public, and the advent of new systems in the form of Galileo and BeiDou have made them an indispensable part of modern life. In addition to its well-known use in vehicle navigation, the system has influenced such diverse fields as land, sea, and air navigation; surveying and geodesy; and large-scale construction projects such as mines, bridges, and tunnels. In addition, in today's railway systems, GNSS, in addition to its functionality related to monitoring moving rolling stock, shows potential applicability in directing and controlling rail traffic. This solution, of course, requires the design and development of a system with an architecture that ensures high-level reliability, the sophistication and cost of which will be commensurate with the required capabilities and accuracy. Today, professional receivers are available on the market that go well beyond the units built into handheld devices intended for general use. Many well-known companies specialize in providing advanced and professional satellite navigation equipment for aircraft and ships. Among the solution providers mentioned are names such as Garmin, Magellan, TomTom, etc., which also provide models for the general market, including drivers, hikers, boating enthusiasts, etc. The above represents the potential for future development of GNSSs in rail transportation. The GNSS receiver operates in the microwave spectrum band, with a dedicated microprocessor and memory to display its position in relation to the corresponding geodetic grid. Although the principle of the system is unidirectional distance measurement, in which the propagation times of the signals reaching the receiver from the satellites are used to measure the distance between them, it is not necessary to have an atomic clock on the equipment of an object positioned using GNSS. The above, as already mentioned, is achieved by calculating the signal propagation delay, and these calculations are called pseudo-range. The task of the control segment on the ground is to apply corrections as needed. The actual ranges must be corrected for receiver clock errors. This is where the number of satellites is critical—not only does it allow for global coverage, but it also introduces redundancy of erroneous pseudo-coverage vectors, which generally do not coincide with the receiver's position, but if the clocks of the satellites are in perfect synchronization, it should require only one correction, namely, the correction of the receiver's clock to coincide. Of course, in practice, there are unavoidable errors in all measurements, and the best solution is that when taking into account the pseudo-distance to multiple satellites, a correction can be found to the receiver clock to minimize the spread in the calculated positions. One of the main functions of the receiver's microprocessor is to calculate this clock correction. It follows that just as the accuracy of a measurement can be improved by repeating it, the accuracy of a position fix in three dimensions is improved by acquiring signals from multiple satellites, but the system is designed so that at least four satellites are fully visible at all times from any point on Earth [67].

Figure 9 shows a simplified GNNS architecture with an indication of transmission to the user segment.

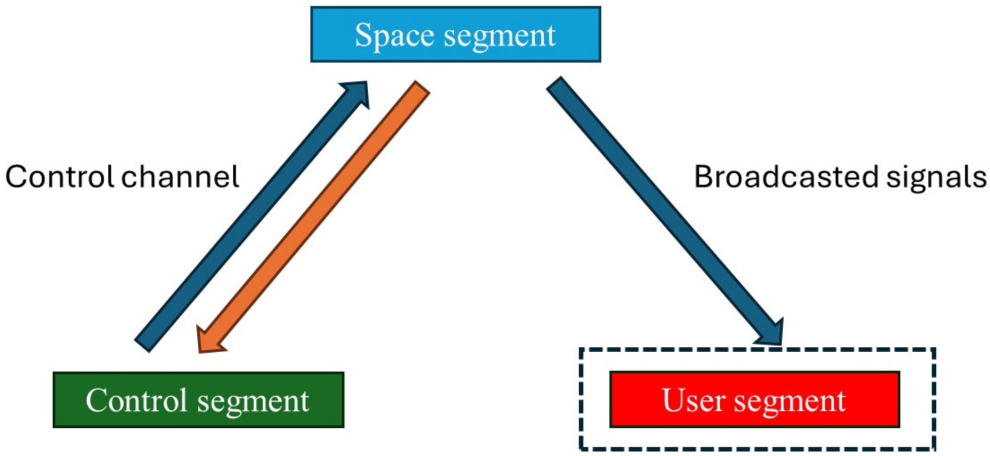

Figure 9. Simplified diagram of the system architecture. Prepared on the basis of [70].

3.6. Smart Train

The rail industry, which is constantly improving standards for rail safety, operational efficiency, and the quality of passenger services, is expected to be a potential market for the development of GNSSs already in use and, above all, the implementation of new solutions. These concepts are mainly based on the penetration of information and telecommunications technologies into the railway environment. One of these concepts is the construction of signaling and train control systems, preferably without trackside equipment. The goal of this concept is to transfer decision-making from the tracks to train-related systems and create so-called distributed intelligent train control systems. In other words, this means making trains potentially intelligent in some elements of the transportation process in the rail industry. This concept will ultimately reduce investment, operating, and maintenance costs, as the introduction of intelligent yet partially or fully autonomous trains will help optimize and reduce the human factor, which in many cases can contribute to causing overuse of vehicles and railway infrastructure (for example, imprecise braking of the train set). A fully autonomous train eliminates the need for staff to drive the train. The above can favorably affect the efficient use of rail transportation, which can translate into a competitive nature in relation to other modes of transportation [71].

Table 5 presents the relationships and functionality of the various segments of GNSS systems.

Table 5. Synthetic comparison of segments.

Segment	Characteristics	Functionality
Space	A constellation of satellites equipped with atomic clocks	– Localization of an object based on the measurement of the difference in propagation delay of radio signals from different satellites – Time synchronization of atomic clocks – Taking into account the error of the atomic clock – For three-dimensional measurements, it is necessary to use at least signals from 4 satellites
Ground	A network of ground installations operated by MCS supported by globally distributed monitoring stations equipped with atomic clocks and GNSS receivers	– Central operational control of the entire system – Tracking the trajectories of individual satellites of the constellation – Monitoring navigation transmissions, analyzing ephemeris – Monitoring system parameters and the status and integrity of the satellites' on-board systems – Taking corrective action in case of identified failures and deviations from the assumed parameters
User	GNSS receivers operating in the microwave spectrum band with dedicated microprocessors and cache memory	– Unidirectional distance measurement – Display of object position in relation to geodetic grid – Calculation of atomic clock correction by correcting actual ranges

4. Overview of GNSSs

A system of satellites that provides autonomous geospatial positioning with global coverage is called satellite navigation. GNSS includes several existing systems, such as GPS, GLONASS, Galileo, and Beidou. These systems are supported by space-based augmentation systems (SBAS) or ground-based augmentation systems (GBAS). Examples of SBAS include the US Wide-area Augmentation System (WAAS), Europe's Geostationary Navigation Overlay System (EGNOS), and Japan's Multi-functional Transport Satellite (MTSAT). These systems augment existing constellations of satellites in medium earth orbit (MEO) with geostationary (GEO) or geosynchronous satellites [72].

These systems combine aspects of localization and navigation using satellite technology and the telecommunications medium. They are becoming increasingly interesting for emergency services, as well as in passenger service applications (emergency callouts, road navigation, information transmission, etc.). Studies have shown that applications developed for road transportation can also be implemented in a rail environment. Nevertheless, there is a growing need to develop low-cost localization systems for satellite-based applications, such as traffic guidance control, for low-density railways. For these applications, system performance and reliability depend on parameters such as positioning accuracy, availability, and integrity [73].

The first GNSSs (GPS and GLONASS) were designed to meet the military's needs for accurate navigation on land, sea, air, and space, but since satellites now transmit unencrypted, freely available civilian signals, applications in the same environments have taken root in modern life. Therefore, today, it is possible to distinguish between military and civilian user satellite positioning applications. There are significant differences between the commercial and military GNSS markets, and the size of the market is changing in a fluid fashion. The number of user receivers in maritime and rail transportation and road transport is seven times larger in 2020 than in 2006. The largest and widest commercial opportunities are in the use of satellite systems for data transmission. An example is the Japanese market, where the deployment of satellite systems in the form of QZSS was aimed at providing positioning and data transmission services in mountainous and urban environments. A particular area of interest in terms of research and development by the Japanese satellite industry market is the provision of navigation services to address the problem of insufficient visibility of GNSS satellites in metropolitan areas, which, according to research, is the biggest problem in the use of GNSS positioning [74,75].

GNSS standards specify the required signal accuracy in space for various operating conditions. They specify in detail the accuracy limits for warnings. If these limits are not exceeded, the user will not receive a message. Space signal accuracy requirements are also defined for SBAS and GBAS. The requirements for GNSS must match those of other systems that are currently in use [76]. Figure 10 shows a simplified way of locating objects in area.

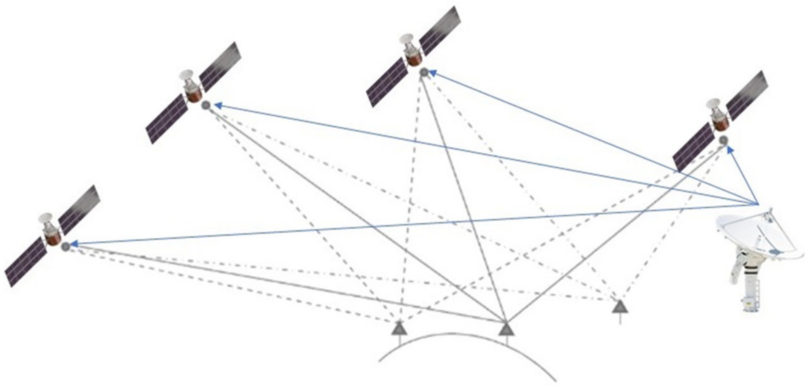

Figure 10. Positioning using GNSS. Prepared on the basis of [72].

4.1. GPS

GPS is a space-based positioning and navigation system that provides three-dimensional positioning with accuracy to within a few meters, anywhere on or near Earth. It was designed for military use to provide the greatest possible accuracy in locating objects in space. The development of the system has made it possible to use GPS for commercial applications as well. Since the discontinuation of selective availability, civilian users have been able to use a signal whose predicted position accuracy has improved with each successive generation of satellites used. GPS satellites emit a signal that contains the transmission time, the satellite's position, and its identifier, along with other information. The signal transmission time determines the distance between the GPS receiver and the transmitting satellite. A receiver that is within range of four satellites is able to determine the receiver's three-dimensional position while eliminating the receiver's clock error [77,78].

4.1.1. GPS System Architecture

The GPS architecture is divided into three segments: space, ground, and user segments. The GPS uses the distance method of measuring the navigation parameter. The idea of this method is to measure the distance to at least three known measurement points—satellites—whose locations are known to the user at any time. The condition for the implementation of this method is to maintain the straightness of the propagation of radio waves and the constant speed of their propagation in the electromagnetic environment. The navigation parameter is measured by measuring the propagation time of radio signals of known structure, transmitted by the navigation satellite, and received by the user's receiver. The prerequisite for the correct operation of a navigation system using the distance method is a follows [79,80]:

- Elimination of the resulting time scale error in the receiver;

- Accurate synchronization of the time scale of the user's receiver with the time scale of the GPS system.

4.1.2. GPS Space Segment

The space segment is composed of a constellation of 24 satellites, including 21 operational and three backup satellites. Four of satellites are evenly distributed in six orbital planes, inclined at 55°. The difference between the ascending nodes of each orbital plane is 60°, and the difference in latitude arguments for satellites on the same orbital planes is 30°. This ensures that at least four GPS satellites can be seen at anytime and anywhere in the world. The average orbital altitude of GPS satellites is about 20,200 km, and their orbital period is about 11 h 58 min 2 s [81].

4.1.3. GPS Ground Segment

The ground segment, referred to as the control segment (CS) within the GPS system, consists of four main subsystems: main control station (MCS), alternative main control station (AMCS), ground antenna network (GA), and a network of globally distributed monitoring stations (MSs). The MCS is located in Colorado and is the central control node for the GPS satellite constellation. Operations are maintained 24 h a day, seven days a week year-round by the highly trained staff of 2 SOPS. MCS is responsible for all aspects of constellation command and control, including the following [69]:

- Routine monitoring of the status of the satellite bus and cargo;
- Satellite maintenance and subsystem anomaly resolution;
- Support for launching, decommissioning, and disposal of satellites;
- GPS performance management to ensure compliance with all performance standards;
- Message operations as required to maintain performance in accordance with standards of accuracy and integrity;
- GPS anomaly detection and response;
- Communication with military GPS users.

The GPS uses a variant that simultaneously measures pseudo-distance relative to as many satellites as necessary to determine position coordinates and correct the time scale in the user's receiver. Knowing the distance to one satellite makes it possible to determine the position surface in the form of a sphere on which the object is located. Determining the distance to a second satellite determines a second position surface, which is also a sphere. The intersection of the two position surfaces forms a position line in the form of a circle. The intersection of this circle with the third position surface, determined by measuring the distance to the third satellite, determines two points, one of which is discarded as improbable. GPS is used to determine the position of objects in three-dimensional space, so the procedure must use distances from three reference points. The GPS uses satellites moving in circular orbits around Earth as reference points [79].

4.2. GALILEO

The European Union, in close cooperation with the European Space Agency, has developed its own system that meets the criteria of accuracy, reliability, and safety called Galileo. The system will be controlled by civilian authorities and will cooperate with GPS and GLONASS. It will provide real-time positioning and timing services at various levels of accuracy, integrity, and availability. Other than existing satellite navigation systems, Galileo is a suitable system for safety-critical applications such as landing aircraft, guiding cars, tracking hazardous materials, and controlling rail traffic [78,82].

4.2.1. GALILEO System Architecture

The architecture of the Galileo system consists of space and ground segments, with the possibility of specifying additional stand-alone sub-segments with specific services in the ground segment. The user segment is considered a separate component, the implication being that this segment will interact with all other system components [79].

4.2.2. GALILEO Space Segment

The basic configuration of the Galileo constellation is defined as a 24/3/1 Walker constellation: 24 nominal satellites in medium Earth orbit are arranged in three orbital planes, with their ascending nodes evenly spaced at 120-degree intervals, inclined at 56 degrees to the equator. Each orbital plane contains eight satellites evenly spaced in the plane, at 45-degree latitude intervals. The angular offset between satellites in two adjacent planes is 15 degrees. The constellation is supplemented by spare satellites, which can be moved to any nominal slot in any plane of the orbit as needed for maintenance or service evolution [76,83].

4.2.3. GALILEO Ground Segment

Both the ground control segment and the ground mission segment, along with the following infrastructure, are included in Galileo's ground segment:

- Galileo Control Centers (GCCs), implementing ground control functions and ground missions at each location;
- Galileo's worldwide network of sensor stations (GSS), which collects and transmits Galileo measurements and data in real time;
- A worldwide network of Galileo Uplink Stations (ULS) that distributes and transmits mission data to the Galileo constellation;
- A worldwide network of telemetry, tracking, and control stations (TTC stations) that collect and transmit telemetry data generated by Galileo satellites and distribute and transmit control commands required to maintain the Galileo satellites and constellation under nominal operating conditions.

4.3. GLONASS

GLONASS is a global satellite navigation system that provides positioning, navigation, and timing services on a continuous, worldwide basis. GLONASS receivers calculate their position in the GLONASS reference system using satellite technology, based on triangulation principles. The space segment's main functions are transmission of radio navigation signals and storage and retransmission of navigation messages sent by the control segment. The GLONASS ground segment (also referred to as the control segment or operational control system) is responsible for the proper operation of the GLONASS system [78].

4.3.1. GLONASS System Architecture

The GLONASS system architecture consists of three segments:

- Space segment;
- Control segment;
- User segment.

All of these segments work together to provide users around the world with accurate three-dimensional positioning, timing and velocity data [70].

4.3.2. GLONASS Space Segment

The GLONASS space segment, evenly distributed across three orbital planes with an inclination of 64.8°, consists of 21 operational satellites and three backups. The longitudes of the ascending nodes of each plane differ by 120° from plane to plane. In each orbital plane there are 8 satellites 45° apart in latitude. At an altitude of 19,100 km, the orbital period is 11 h 15 min and 44 s. In September 2016, the number of operational satellites in orbit was increased to 27, of which 24 are GLONASS-M and GLONASS-K1 satellites with full operational capability [81].

4.3.3. GLONASS Ground Segment

The GLONASS ground segment's main components include the GLONASS system control center (SCC) and central clocks (CC), telemetry, tracking and command stations (TT and C), and uplink stations, as well as unidirectional monitoring stations and satellite laser ranging (SLR) stations. All major ground segment assets are located on Russian territory [84].

Plans for the development of the ground control segment (GCS) before 2020 include all core elements of the GCS to improve its performance, including upgrading passive measurement and computing stations, the main master clock, inserting measurement stations and expanding the network of laser measurement stations. The upgraded GCS will additionally include the following [85]:

- Onboard Inienatellite Measurement Equipment (OIME) ground control loop that provides orbit and clock data input to the navigation satellite;
- A network of passive measurement stations (PMS) for operational bits and clock data as part of the GCS to improve accuracy and integrity.

4.4. BeiDou

The BeiDou Satellite Navigation System (BDS) provides a range of services resulting from its functionality. Currently in operation, the BeiDou is the third phase of China's satellite navigation system. In addition to the positioning, navigation, and timing (PNT) service provided by all GNSS, BDS also offers regional message communication, global short message communication, global search and rescue (SAR) service, regional precision point positioning (PPP) service, built-in satellite extension service (BDS-BAS), and space environment monitoring function [78,86,87].

4.4.1. BeiDou System Architecture

In the case of a positioning request, MCS determines the user's location based on the measured signal rotation time and the user's altitude, which is taken from a digital database stored at MCS or provided by the user. The resulting location information is then transmitted back to the user via an outbound signal. For short messages, the message is sent to the addressee by MCS via the outgoing signal. For time requests, the user's exact time adjustment is calculated by MCS and sent to the user via an outbound signal. Based on the time correction, the user adjusts the local clock, synchronizing it with the MCS clock. Requests can be sent, and location information and short messages can be received by user terminals. They can operate in two modes: one mode involves receiving one outgoing signal and transmitting incoming signals via two satellites, while the other mode involves receiving outgoing signals from two satellites when the user is in the common coverage area of two satellites, and transmitting incoming signals via only one satellite. Based on the time difference between the two received outgoing signals and the service re-task transmitted via one satellite, MCS measures the pseudo-distance from the user to the two satellites and calculates the user's position [88–90].

4.4.2. BeiDou Space Segment

BeiDou's regional satellite navigation system consists of three groups of satellites: GEO, IGSO, and MEO. The constellation includes 44 satellites: 7 in geostationary orbits (GEO), 10 in 55° inclined geosynchronous orbits (IGSO), and 27 in medium earth orbit (MEO). In addition, eight satellites (four in medium earth orbit, two in geostationary orbit, and two in inclined geosynchronous orbit) are undergoing testing or launch. The constellation is designed to provide worldwide coverage. The lifetime of the satellites is eight years. The platform and navigation payload of all three types of satellites are essentially similar, but there are differences in the equipment of each GEO satellite [88].

4.4.3. BeiDou Ground Segment

The BDS ground control includes the main control station (MCS) and over 20 calibration stations. The MCS is responsible for receiving incoming signals, determining the satellite's orbit, transmitting signals, ionospheric correction, determining user location, and sending short messages to specific users. Calibration stations provide basic measurements for orbit determination, differential positioning over a large area, and calculation of user altitude.

The OCS BDS provides command, control, and operation functions for three types of satellite constellations. The main functions of the OCS BDS are as follows:

- Establishment and maintenance of data coordinates;
- Maintaining a time reference point;
- Measuring time synchronization;
- Precise determination;
- Prediction of orbits;
- Predicting the shift of the satellite clock;
- Processing of extended data;
- RDSS information processing;
- Monitoring, processing, and predicting ionospheric delays;
- Integrity monitoring;
- Uploading and downloading navigation messages.

The OCS workflow can be described as the process of collecting data related to satellites and ground stations, processing and analyzing that data, managing communications between satellites and ground stations, and sending operational commands to ground stations [88].

4.4.4. User Segment BeiDou

The BeiDou user segment consists of BeiDou user terminals that receive BeiDou navigation signals, determine pseudo-ranges, and solve navigation equations to obtain their coordinates. There is also international cooperation on compatibility and interoperability between BeiDou and other GNSSs, with the goal of bringing terminals compatible with other GNSSs [91].

4.5. Quasi-Zenith Satellite System

The Quasi-Zenith Satellite System (QZSS) is a regional satellite navigation system implemented by the Japanese government since 2003. It was originally intended to augment the US GPS in Japan with three satellites. The satellites have an orbital period of 23 h 56 min, a higher orbit inclination, and low eccentricity, which optimizes visibility at high elevation angles in Japan. This is crucial for urban and mountainous areas where GPS signals are insufficient. Each of the three IGSO satellites flies over Japan for eight hours, ensuring continuous availability of navigation signals.

The first QZSS satellite, QZS-1, was launched on 11 September 2010. After successful testing, on 30 September 2011, the Japanese government announced the establishment of a constellation of four QZSS satellites as national infrastructure by the end of 2010, with a goal of expanding to seven satellites by 2023. The National Space Policy Secretariat (NSPS) in the Cabinet Office is responsible for implementing the system. In 2013, a tender was launched to establish a ground control segment and provide services from 2018 to 2033 under the Private Finance Initiative (PFI) project [92].

4.5.1. QZSS Architecture

The QZSS consists of a space segment and a ground segment. The space segment initially consists of a single QZS. The ground segment consists of master control station (MCS), a monitoring station (MS), tracking and control stations (TCSs), and systems from other national research institutes. About 10 MSC stations have been deployed in Japan and overseas to more accurately estimate and predict the QZS orbit and clock [92].

4.5.2. QZSS Space Segment

The QZSS consists of IGSO and GEO satellites with an orbital period of 23 h and 56 min, synchronized with the Earth's rotation. The IGSO satellites are located in three orbital planes, offset by 120° in RAAN and latitude arguments, providing an identical ground track and continuous availability of one satellite every 8 h.

To optimize visibility around Japan, the orbits have an inclination of 43° and a slight eccentricity, with an apogee in the north and a perigee argument of 270°. The central longitude of the ground track is 135° east. The asymmetric orbit provides a good compromise between service availability, link properties, and resilience, compared to a fully symmetric orbit and a teardrop-shaped orbit [92].

4.5.3. QZSS Ground Segment

The MCS is the focal point for the execution of QZS-1 navigation operations and performs the following functions:

- Estimating the orbit and clock offset;
- Generating navigation messages;
- Remote control;
- Monitoring the quality of the navigation signal;
- Generating status or warnings.

Monitoring stations have been located in Japan and in Asia and Oceania to receive QZSS and GPS signals for precise orbit and clock estimates. Some of these stations outside Japan have been established in cooperation with international organizations. The monitoring stations receive L-band navigation signals from the QZSS and GPS constellations and then transmit the raw data to the MCS via a ground or satellite communications link.

The monitoring station (TCS) is responsible for QZS-1 satellite bus operations. This includes, but is not limited to, the following functions:

- Performing orderly operations;
- Remote control;
- Planning and maintenance;
- Integration of all system operations.

The main ground station, located on Okinawa, ensures continuous operation of the QZSS, which is constantly visible there. Due to regular typhoons during the summer season, the station has been equipped with two redundant high-gain 7.6 m diameter antennas and a protective radar dome to ensure uninterrupted operation even in severe weather.

The station, responsible for time synchronization, measures the difference between the satellite's on-board clock and a highly stable ground reference point, and performs data transmission operations. Based on the TMS measurements, UTC (Coordinated Universal Time) time offset parameters and a set of GPS-QZSS time offsets (GQTO) are generated for the QZS-1 navigation message [92].

4.5.4. QZSS User Segment

Signals that complement the GPS positioning service are designed to minimize the need for modifications to the user's hardware. Receivers can seamlessly receive and track GPS and QZSS signals, decode their navigation messages, and calculate a user's position, speed, and time based on a combination of GPS and QZSS observations. There is a difference in the handling of GPS and QZSS clock information between the systems, requiring the user to take into account the distortion between the signals [92].

4.6. Other Systems

A new and different approach is to use a constellation of satellites in low earth orbit (LEO) to dramatically reduce communication delays. The first large-scale deployment of this kind is the Starlink constellation, now supporting more than two thousand satellites. The commercial service was launched in beta in October 2020 in the United States, and from 2021 in European countries. According to the operator, it provides internet access with latency of 20 ms and speeds of 100 to 200 Mbps. Because it is a new service, its operation and performance have not yet been fully studied. One of the few works has been proposed by [93], which shows how Starlink performance changes at different benchmarks. Another paper focuses on how the performance of a single Starlink viewpoint changes when accessing globally distributed resources, under heavy network load, using TCP and QUIC transport protocols [94]. SpaceX has already launched the first satellites of its Starlink constellation, with a target number of 42,000. Earlier this year, Blue Origin announced its intention to create its own satellite internet constellation (with more than 3000 satellites), and OneWeb has already launched the first satellites in its venture. Both established companies and startups are launching large networks of small satellites. Cheaper, easier to manufacture, and cheaper to send into space, small constellations of satellites collectively cover much more of the Earth than standard satellites [95].

The main difference between the two approaches is the distance between the satellites: while geosynchronous satellites are 35,000 kilometers apart, LEO satellites are much closer. For example, Starlink has five orbital shells, the closest of which is only 550 kilometers away. This much shorter distance allows for much lower latency, comparable to traditional broadband providers. However, this approach also requires a much larger number of satellites, since each satellite is only in sight of a ground station for a short time. This has led to the development of so-called "mega constellations" of satellites. Because there are many more satellites, overall network capacity is also higher, and Starlink promises much higher bandwidth than traditional satellite internet providers [96].

Table 6 shows some of the more important parameters characterizing GNSSs. Especially noteworthy is the QZSS, which functionally provides coverage only in southeast Asia and Oceania. The above implies that this system should not be considered global; however, with regard to the issue at stake, the parallel use of more global systems in rail vehicle positioning, this system is included in the current review. The other systems provide positioning capabilities for the entire globe. Consequently, the use of any of those mentioned makes it possible to position an object regardless of its location. However, as demonstrated in this article, for the highest possible safety parameters, it is far preferable to use systems equipped with GNSS receivers using more than one satellite positioning system. Within the framework of this article, none of the characterized GNSSs are indicated as dedicated to railway applications, since the choice depends on a number of factors, including geopolitical factors, which may be the main basis for system selection, regardless of the technical aspects of the system in question. Another reason for choosing a particular system may be geographic location, as mentioned above with regard to the QZSS.

Table 6. Parameters of satellite navigation systems.

Reference Orbit Parameter	GPS	Galileo	GLONASS	BeiDou	QZSS
Number of satellites (current usable)	38	28	26	35	4
Orbit semimajor axis [km]	~20,200	~23,200	~19,100	~21,500	~42,000
Orbit eccentricity	<0.02	<0.16	<0.04	0.00	<0.08
Orbit inclination [deg]	55.0	56.0	64.2–65.6	55.0	43.0
Date of origin	1970s	2000s	1980s	1990s	2010s

The Starlink system is not included in the above table due to its completely different space segment architecture. In addition, this system is dedicated primarily to data transmission; thus, it is not included in satellite positioning applications.

5. GNSS Implementation

To increase the popularity of satellite positioning in rail guidance and control, the European GNSS Agency (E-GNSS) is working with stakeholders in the rail and space industries. The deployment of GNSS within railway systems is possible in the area of the European Train Control System (ETCS), which is currently being implemented both in Europe and beyond as one component of the European Rail Traffic Management System (ERTMS). Under ETCS, train positioning is currently based on determining the position of a rail vehicle using an odometer, whose potential measurement error is corrected based on so-called balises, which are physical elements mounted at specific intervals along the railway tracks. All information is exchanged between the ETCS on-board system and the RBC (Radio Block Center) trackside system via a radio communications network. The train transmits two pieces of information to the RBC: its location and confirmation that it has not lost any cars. This information is called "integrity" in the rail industry and is a safety feature. The potential of using GNSS for railway applications in this case manifests itself in the ability to replace, wherever possible, physical balises with virtual balises (VBs) based on precise GNSS positioning, without any operational or safety implications for ETCS [97–99].

The ETCS, due to its functionality, is divided into several levels, which include Level 0, Level 1, and Level 2. In the review in question for the ETCS system, Level 3 additionally appears. The above is due to the fact that the review article is developed on the basis of the literature issued before the update of the so-called Technical Specifications for Interoperability (TSI) issued on 28 September 2023. Within the framework of the TSI in question for the Control–Command and Signaling Trackside Subsystem (CCS TSI), ETCS is expected to migrate to baseline 4, which does not include ETCS Level 3 in the further development process. However, due to the nature of this review article, ETCS Level 3 (ETCS L3) will be considered in the remainder of this article; Level 3's operating logic enables the implementation of GNSS functionality in train positioning and with regard to path setting, consisting of determining the destination and ensuring safe passage along routes in areas where there may be conflicts (intersection, junction, railway crossing). The above refers to the so-called dependency systems (IXLs), the purpose of which is to verify the possibility of the route along with securing the routing—in accordance with safety logic—of each relevant part of the infrastructure until all trains have passed through all sections of track reserved for the route. Thus, the system receives information on the occupancy of a section from trackside equipment on input (e.g., obtained from axle counters or track circuits), then sends commands to trackside equipment based on relay or computer devices to make automatic adjustments, and transmits free clearance information to the train. The latter information constitutes the so-called permit to run (MA). The MA is transmitted via radio messages by the Radio Block Center (RBC) to an on-board device built into the driver's cab. Dependency systems are traditionally trackside national systems based on national signaling rules, but they are also under discussion to harmonize their operation and interfaces, especially with ETCSs [63,100].

The IXL operating logic described above is characterized by features that limit the possibility of optimal use of the railway infrastructure. A method of improving the efficiency of the control subsystem is to implement the so-called moving block spacing, the boundaries of which are not defined in a fixed way through reference points of a certain route kilometer distance. The boundaries of the moving interval change dynamically depending on the current traffic situation, and the distance between trains is a variable value that is the resultant of a set of current information on the position of individual trains and their speed. The movement of a rail vehicle in the interval of the braking distance, which is provided by systems that allow for continuous updates of information and transmit them to the vehicle in the form of an MA permit, which contains, in basic terms, a set of elements that determine its validity (km of the route to which the train can move) and the maximum speed granted in the MA. The differences resulting from the movement of a rail vehicle in fixed block spacing and moving block spacing are shown in Figure 11.

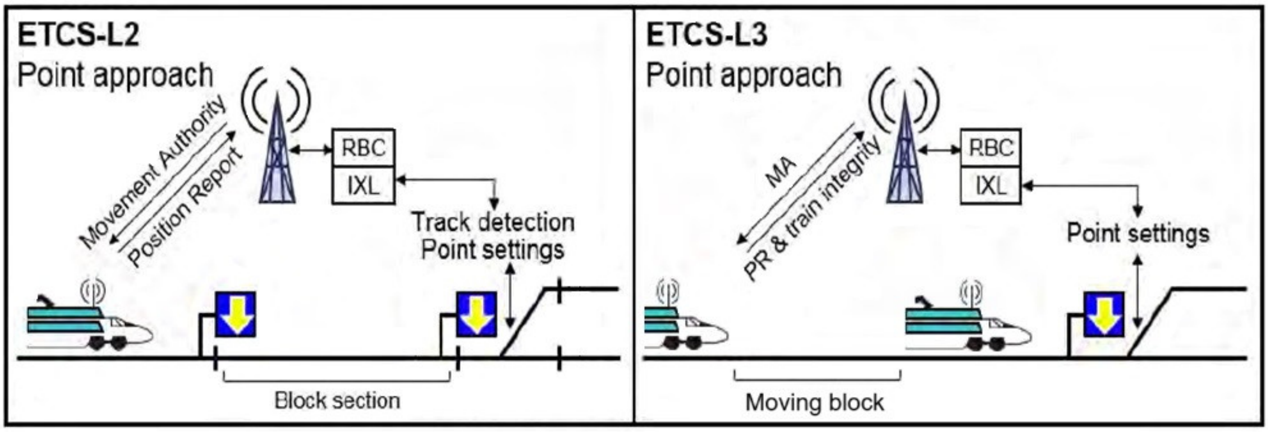

Figure 11. Functionality of the ETCS L2 and L3 system with respect to fixed and moving block spacing. Prepared on the basis of [100].

In functional terms, a movable block spacing is a continuous extension of the section of track on which a train with an issued MA can travel, along with information on the permissible limiting speed at which the required distance between the end of the preceding train and the head of the train for which the MA was issued is maintained, which is not shorter than the braking distance of the train for which the MA was issued [101,102]. The principle of mobile spacing is shown in Figure 12.

The use of mobile spacing is possible only when the exact position of rail vehicles in a given area is known. The potential for using GNSS in the functionality of ETCS L3 offers such a possibility. However, it should be taken into account that technological changes to apply GNSS to ETCS L3 will also affect the logic rules of the dependency systems to achieve functionality in accordance with the moving distance principle [100,103].

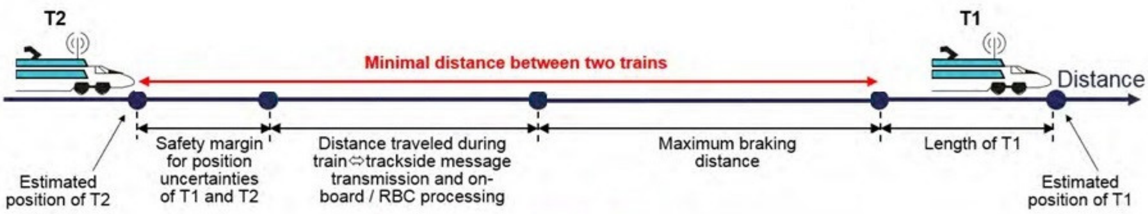

Figure 12. Principle of maintaining safe distances between train corollaries. Prepared on the basis of [100].

The implementation of satellite positioning systems will allow for the protection of runs with moving block spacing in railway traffic control systems. However, it should be borne in mind that a train, unlike an airplane, moves close to various objects that are considered obstacles to signal transmission. Consequently, various solutions have been developed to deal with these effects. One classic solution is based on an odometer and the use of GNSS positioning to calibrate the odometer error in case of discrepancies. However, most solutions in the literature are based on the fusion of heterogeneous information. Their principle is to combine heterogeneous sensors to use the advantages of each sensor to calculate position, velocity, and time. In view of the above and the complex environmental conditions along the railway alignment, positioning technology should develop towards integrated GNSS/INS. In completed studies, it has been shown that GNSS does not achieve continuous and stable positioning, especially in urban areas. It is also important to keep in mind GNSS data latency problems, which can cause further inaccuracies in rail vehicle positioning. A potential solution to the problem of low GNSS accuracy could be to use a system to combine the absolute positioning data of GNSS receivers with the relative data of sensors built on the rail vehicle, in order to realize precise vehicle positioning during GNSS outages. First, the system extracts the original data from all sensors and then requires pre-processing to convert these data into the variables necessary for the process of determining the correct location. The next step is data fusion. The results of the pre-processing are fed into the model to obtain the best estimate of the output system. The above solutions indicate the need for additional sensors built on rolling stock, while minimizing the development of costly trackside infrastructure. GNSS positioning introduces a new possibility for providing the required performance that has not been possible to implement until now. With conventional solutions for detecting and locating rail vehicles on the rail infrastructure, ETCS requires the use of physical balises, which are fixed in the track with their exact location determined. The use of GNSS, i.e., the use of an embedded wireless system, combined with the use of digital maps, makes it possible to dispense with the use of physical balises and use so-called virtual balises, whose location is specified on a digital map. For the system to work like a physical balise, it should detect when a train reaches a virtual balise previously identified and stored in the virtual balise map database. Before migrating toward virtual balises, the system must guarantee that the train ahead will pass (in its entirety) through the virtual balise to ensure that the track between the locations in question is free. The above is one of the bases for justifying the implementation of a GNSS. Reducing the use of trackside equipment has a positive effect on financial aspects, as well as on the environment. When implementing this type of solution, however, it should be borne in mind that railway operating rules, regulations, and standards are not structured in terms of operations in this regard [26,103].

6. Discussion

A review of the current state of the art in potential implementations of Global Satellite Positioning Systems in rail transportation, with a particular focus on train guidance and control systems, illustrates the widespread interest in the application of positioning of rail vehicles using satellite systems. The main direction of research and implementation projects revolves around the European Train Control System, one of the areas of development of which is the application of mobile block spacing. The potential benefits of using mobile spacing are widely reported in the literature, and in conjunction with the issue at hand, issues are being raised regarding the application of precise localization of rail vehicles on railway infrastructure. In this context, GNSSs are pointed out as one of the potential systems to be used in the guidance and control of rail traffic. The literature considered in this review describes in detail the solutions involving the use of GNSSs, indicating the need to specify the technical requirements, which are the basis for the design and construction of guidance and traffic control systems, in which the module responsible for locating rail vehicles would be based on satellite solutions. The above requires the clarification of technical standards and the definition or adaptation of the existing regulations on railway traffic guidance.

The issue of GNSS application is often combined with the use of multi-sensor on-board equipment, the architecture of which is based on the use of satellite positioning along with the use of a so-called odometer, which is part of the equipment of rolling stock moving under the indications of the ETCS. The literature base of the state-of-the-art review takes into account a number of items characterizing the above solutions, which can form the basis for the implementation of satellite systems on the railway.

Another issue, taken into account in part of the literature items, is the concept of creating and using a digital map in directing and controlling railway traffic. In the commercial application of satellite navigation, the map provides a reference point for locating a vehicle in space. Similarly, in the subject of the use of satellite positioning in rail transport, it is necessary to create a digital network of railway infrastructure. The authors of publications describing the above issue indicate that there is a very large gap in this area, which may translate into difficulties and limitations in the possibility of implementing GNSS in railway solutions. The above is highlighted primarily in terms of existing infrastructure, for which economic considerations may preclude the possibility of creating a digital map.

Analyzing the literature base of this review, it can be observed that most of the publications do not describe issues related to the accuracy of positioning of rail vehicles and the risks of using GNSS. The most frequently cited information, indicating the potential positioning accuracy for particular GNSSs, is due to the duplication of information on positioning accuracy given as one of the parameters of a given satellite system. Another reference is the parameters derived from the characteristics of global satellite systems in relation to particular branches of commercial use, including use in transportation in the broadest sense. In a small part of the cited literature items, the above issue is addressed, and even more rarely are attempts at research in this area indicated, which is a potential basis for the development and conduct of further studies of satellite positioning accuracy of rail vehicles. In addition, it should be noted that the literature to date does not accurately describe the issue of how and what criteria are used to assess the safety of using positioning systems in rail transportation. As indicated in this article, for railway and aeronautical applications, there are different approaches to risk assessment. Despite the partial convergence of the characteristics of the evaluation criteria, differences are still observed in the approach to the criterion both formally and technically. Therefore, there is a need for development and research in the context of defining common criteria for safety assessment in the application of GNSSs in traffic guidance and control.

The characteristics of the research carried out and the areas requiring development for the implementation of additional or new research included in this article are intended to guide the further process of analyzing the possibility of using satellite systems in aspects of optimization and safety of railway traffic. Conclusions, observations, and potential directions of development should form the basis for the indicated analysis, and their use is addressed to current and future institutions responsible for the creation of formal, as well as normative requirements and regulations, allowing to standardize uniform documents, which are the basis for further implementation of projects in the rail transport industry sector. However, it should be borne in mind that this article is based on the acquired knowledge from the literature review and does not refer to the development plans of individual countries or the European community. The above results in the fact that potential intentions arising from the adopted development strategies of the railway infrastructure managers of individual countries have not been determined; thus, it is not possible to determine whether the implementation of GNSSs in rail transport is proceeding in a systematic manner or is being abandoned in favor of the development of other rail vehicle positioning solutions.

7. Conclusions

Paraphrasing the words of Tim Marshall included in one of his books, entitled The Future of Geography: How Power and Politics in Space Will Change Our World, it can be said that signs that space will play a major role in rail transportation of the twenty-first century have been evident for some time. This is evidenced not only by the number of literature items, but also by a number of ongoing projects and studies aimed at developing solutions to implement the functionality of Global Navigation Satellite Systems in railway applications. An example is the described projects APOLO, GADEROS, LOCOPROL, GaLoROI, 3inSat, NGTC and Shift2Rail IP2, the assumptions of which were or are aimed at the development of the railway industry in terms of automation and autonomy of the implementation of traffic processes. In the literature relating to the above programs, the authors mostly define the assumptions and guidelines for the implementation of the projects, with little description of the technical assumptions.

In this review, the focus is on literature items published in the years from 2000 to the present. According to the presented review cross-section of literature items, the largest trend in the publication of articles on GNSS implementation in railway solutions has been observed since 2015. The above may be due to the fact that in the current period, new projects and programs related to the development of railway systems were launched, among which one of the new areas was the implementation of satellite positioning systems in railways. The above and the apparent development combined with the widespread use of satellite positioning combined with the expansion of the functionality of satellite systems in commercial applications became the basis for reconsidering the implementation of positioning in railway systems. It should be noted that the apparent decrease in the upward trend in the publication of articles on GNSS in railways in 2021–2023 is most likely due to the situation associated with the constraints of the COVID-19 pandemic. In contrast, the trend of publications for mid-2024 indicates renewed interest in the subject area.

When considering the possibility of using rail vehicle positioning based on signals from a constellation of space segment satellites, supported by ground segment infrastructure, it is first necessary to determine the area of potential implementation of GNSS in railway infrastructure. Based on the projects and studies carried out to date, it can be observed that the most frequently indicated area for GNSS application is the positioning of rail vehicles for the purpose of moving spacing in ETCS Level 3. For the purpose of running railway traffic, it is necessary to ensure, in accordance with the assumptions of the RAMS criteria, a high level of safety of the system or systems determining the positions of a given rail vehicle in the railway infrastructure. In this context, it should be noted that the criteria for evaluating satellite positioning systems included in the ICAO guidelines differ in terms or have different definitions for converging criteria. The above requires defining the parameters of technical evaluation criteria, consistent for the applications of satellite systems in rail transport, or defining new ones, uniform for both areas.

Obtaining the highest possible level of positioning accuracy for rail vehicles requires continuous and uninterrupted transmission of signals between the satellites of the various satellite constellations and the object, which in the case under consideration is a train moving on the railway lines. At this point, it is important to emphasize the importance of using as many independent GNSSs as possible in positioning, in order to reduce the potential risks arising from a temporary or long-term failure of system operation. The above should be borne in mind first and foremost in the conception, design, and construction of the systems in question, particularly in light of the current situation of the war in Ukraine, where alleged military activities contribute to limitations in the operation of GNSSs. Multi-sensor systems are an example of system solutions for minimizing the risks arising from the limitations of positioning using GNSS. In addition, the impact of additional sensors on the safety and functionality of positioning systems must be taken into account in the context of obtaining the relevant approvals and railway approval documentation, including certification. The above represents a potential risk in the implementation of multi-sensor systems.

Further steps in taking steps to implement GNSS in railway applications should be aimed at specifying the architecture of the railway control system, taking into account positioning using satellite systems, and characterizing operational assumptions, taking into account GNSS as an integral part of the railway guidance and control systems.

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References

1. Severi, S.; Wymeersch, H.; Harri, J.; Ulmschneider, M.; Denis, B.; Bartels, M. Beyond GNSS: Highly accurate localization for cooperative-intelligent transport systems. In Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC), Barcelona, Spain, 15–18 April 2018. [CrossRef]
2. Marais, J.; Meurie, C.; Attia, D.; Ruichek, Y.; Flancquart, A. Toward accurate localization in guided transport: Combining GNSS data and imaging information. *Transp. Res. Part C Emerg. Technol.* **2014**, *43*, 188–197. [CrossRef]
3. Krasuski, K. Application the Single Difference Technique in Aircraft Positioning Using the GLONASS System in the Air Transport. *Komunikácie Ved. Listy Žilinskej Univerzity Žiline* **2019**, *8*, 51–58. [CrossRef]
4. Tiberius, C.; Verbree, E. GNSS Positioning Accuracy and Availability within Location Based Services: The Advantages of Combined GPS-Galileo Positioning. In Proceedings of the 2nd ESA/Estec Workshop Satellite, Noordwijk, The Netherlands, 8–10 December 2004; pp. 1–12.
5. Diani, F.; Sbardellati, F.; Lisi, M. GNSS User Technology: Next generation GNSS-based location technologies. In Proceedings of the European Microwave Conference in Central Europe (EuMCE), Prague, Chech Republic, 13–15 May 2019.
6. Liu, S.; Hu, L. Application of Beidou Navigation Satellite System in Logistics and Transportation. In Proceedings of the International Conference of Chinese Logistics and Transportation Professionals (ICCLTP 2008), Chengdu, China, 31 July–3 August 2008. [CrossRef]
7. Xu, A.; Xu, Z.; Xu, X.; Zhu, H.; Sui, X.; Sun, H. Precise Point Positioning Using the Regional BeiDou Navigation Satellite Constellation. *J. Navig.* **2014**, *67*, 523–537. [CrossRef]

8. Suzuki, T.; Kubo, N. Precise point positioning for mobile robots using software GNSS receiver and QZSS LEX signal. In Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, Tokyo, Japan, 3–7 November 2013. [CrossRef]
9. Bramanto, B.; Gumilar, I. Evaluation of QZSS orbit and clock products for real-time positioning applications. *J. Appl. Geodesy* **2021**, *16*, 165–179. [CrossRef]
10. Dovis, F.; Ruotsalainen, L.; Toledo-Moreo, R.; Kassas, Z.Z.M.; Gikas, V. Recent Advancement on the Use of Global Navigation Satellite System-Based Positioning for Intelligent Transport Systems. *IEEE Intell. Transp. Syst. Mag.* **2020**, *12*, 6–9. [CrossRef]
11. Goolak, S.; Gorobchenko, O.; Holub, H.; Dudnyk, Y. Increasing the efficiency of railway rolling stock operation with induction traction motors due to implementation of the operational system for diagnostic condition of rotor. *Diagnostyka* **2024**, *25*, 2024404. [CrossRef]
12. Burdzik, R.; Nowak, B. Identification of the Vibration Environment of Railway Infrastructure. *Procedia Eng.* **2017**, *187*, 556–561. [CrossRef]
13. Steuer, M.; Krzykawski, M.; Simiński, D.; Chema, W.; Burdzik, R. Train detection methods as the foundation of positioning systems of railway traffic control. *Diagnostyka* **2023**, *24*, 2023305. [CrossRef]
14. Breßler, J.; Reisdorf, P.; Obst, M.; Wanielik, G. GNSS positioning in non-line-of-sight context—A survey. In Proceedings of the IEEE 19th International Conference on Intelligent Transportation Systems (ITSC), Rio de Janeiro, Brazil, 1–4 November 2016. [CrossRef]
15. Marais, J.; Beugin, J. Evaluation Method of GNSS–based Positioning Functions for Safety Applications in Operational Conditions. *Procedia Soc. Behav. Sci.* **2012**, *48*, 806–815. [CrossRef]
16. Wang, X.; Toth, C.; Grejner-Brzezinska, D. A Survey on Integrity Monitoring of GNSS Navigation for Ground Vehicles. In Proceedings of the 34th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2021), St. Louis, MO, USA, 20–24 September 2021. [CrossRef]
17. Costa, N.D.; Piers, R.; Hawley, M.; Fiebelhorn, J.; Styles, J. Economic Benefits of GNSS in Transport Applications. In Proceedings of the 18th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2005), Long Beach, CA, USA, 13–16 September 2005.
18. Sadeghian, P.; Håkansson, J.; Zhao, X. Review and evaluation of methods in transport mode detection based on GPS tracking data. *J. Traffic Transp. Eng.* **2021**, *8*, 467–482. [CrossRef]
19. Khan, D.; Burdzik, R. Measurement and analysis of transport noise and vibration: A review of techniques, case studies, and future directions. *Measurement* **2023**, *220*, 113354. [CrossRef]
20. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *57*, 444–465. [CrossRef]
21. Rövera, S.; Schroeder, M.; Schnieder, E. Satellite based locating in guided traffic. *WIT Trans. Built Environ.* **1998**, *34*, 659–668. [CrossRef]
22. Chrzan, M.; Kornaszewski, M.; Pniewski, R. Methods of Determining the Position of the Train. In Proceedings of the 25th International Scientific Conference, Transport Means 2021, Kaunas, Lithuania, 6–8 October 2021.
23. Beugin, J.; Marais, J. Simulation-based evaluation of dependability and safety properties of satellite technologies for railway localization. *Transp. Res. Part C Emerg. Technol.* **2012**, *22*, 42–57. [CrossRef]
24. Lu, D.; Toro, F.G.; Schnieder, E. RAMS Evaluation of GNSS for Railway Localisation. In Proceedings of the IEEE International Conference on Intelligent Rail Transportation Proceedings, Beijing, China, 30 August–1 September 2013. [CrossRef]
25. Nguyen, T.P.K.; Beugin, J.; Marais, J. RAMS analysis of GNSS based localisation system for the train control application. In Proceedings of the IEEE International Conference on Computing, Management and Telecommunications (ComManTel), Da Nang, Vietnam, 27–29 April 2014. [CrossRef]
26. Marais, J.; Beugin, J.; Berbineau, M. A Survey of GNSS-Based Research and Developments for the European Railway Signaling. *IEEE Trans. Intell. Transp. Syst.* **2017**, *18*, 2602–2618. [CrossRef]
27. Burdzik, R. Application of vibration signals as independent and alternative information channels to support the reliability of positioning and prediction systems for transport means movement. *Eksploat. Niezawodn. Maint. Reliab.* **2025**, *27*. [CrossRef]
28. Jiang, L.; Baigen, C.; Jian, W. Electronic Track Map Building for Satellite-based High Integrity Railway Train Positioning. *Int. J. Smart Sens. Intell. Syst.* **2013**, *6*, 610–629. [CrossRef]
29. Grosch, A.; Crespillo, O.G. Impact of Unknown Digital Map Errors on Satellite-based Navigation in Railway. In Proceedings of the European Navigation Conference (ENC), Dresden, Germany, 23–24 November 2020. [CrossRef]
30. Bures, J.; Vystavel, O.; Bartoněk, D.; Barta, L.; Havlicek, R. Precise Positioning of Primary System of Geodetic Points by GNSS Technology in Railway Operating Conditions. *Appl. Sci.* **2024**, *14*, 3288. [CrossRef]
31. Quddus, M.A.; Ochieng, W.Y.; Noland, R.B. Integrity of map-matching algorithms. *Transp. Res. Part C Emerg. Technol.* **2006**, *14*, 283–302. [CrossRef]

32. Gerlach, K.; Rahmig, C. Multi-Hypothesis Based Map-Matching Algorithm for Precise Train Positioning. In Proceedings of the 12th International Conference on Information Fusion, Seattle, WA, USA, 6–9 July 2009.
33. Wang, P.; Li, W.; Wang, X.; Chu, X. The Method of Train Positioning Based on Digital Track Map Matching. In Proceedings of the MATEC Web of Conferences Volume 246, Beijing, China, 16–20 October 2018. [CrossRef]
34. Liu, J.; Cai, B.-G.; Wang, J.; Lu, D.-B. Track Map–Aided Capture of Virtual Balises: A Compatible Approach to Satellite-Based Railway Train Control. *IEEE Intell. Transp. Syst. Mag.* **2020**, *14*, 233–249. [CrossRef]
35. Chen, W.; Yang, G.; Tu, Y. A Digital Track Map-Assisted SINS/OD Fusion Algorithm for Onboard Train Localization. *Appl. Sci.* **2023**, *14*, 247. [CrossRef]
36. Stallo, C.; Neri, A.; Salvatori, P.; Coluccia, A.; Capua, R.; Olivieri, G.; Gattuso, L.; Bonenberg, L.; Moore, T.; Rispoli, F. GNSS-based location determination system architecture for railway performance assessment in presence of local effects. In Proceedings of the IEEE/ION Position, Location and Navigation Symposium (PLANS), Monterey, CA, USA, 23–26 April 2018. [CrossRef]
37. Chen, X.; Luo, R.; Liu, T.; Yuan, H.; Wu, H. Satellite Navigation Signal Authentication in GNSS: A Survey on Technology Evolution, Status, and Perspective for BDS. *Remote Sens.* **2023**, *15*, 1462. [CrossRef]
38. Durazo-Cardenas, I.; Starr, A.; Tsourdos, A.; Bevilacqua, M.; Morineau, J. Precise vehicle location as a fundamental parameter for intelligent selfaware. In Proceedings of the 3rd International Conference on Through-life Engineering Services, Bedfordshire, UK, 4–5 November 2014. [CrossRef]
39. Reimer, C.; Müller, F.J.; Hinüber, E.L.V. INS/GNSS/Odometer Data Fusion in Railway Applications. In Proceedings of the DGON Intertial Sensors and Systems (ISS), Karlsruhe, Germany, 20–21 September 2016. [CrossRef]
40. Bedrich, S.; Gu, X. GNSS-based sensor fusion for safety-critical applications in rail traffic. *Galileo EGNOS Inf. Cat.* **2016**.
41. Selvi, D.; Meli, E.; Allotta, B.; Rindi, A.; Capuozzo, A.; Rucher, L. Feasibility Analysis of Positioning and Navigation Strategies for Railway and Tramway Applications. *IFAC-PapersOnLine* **2020**, *53*, 15680–15686. [CrossRef]
42. Malakar, B.; Roy, B.K. Train localization using an adaptive multisensor data fusion technique. *Transport* **2019**, *34*, 508–516. [CrossRef]
43. Allotta, B.; D'Adamio, P.; Malvezzi, M.; Pugi, L.; Ridolfi, A.; Vettori, G. A localization algorithm for railway vehicles. In Proceedings of the IEEE International Instrumentation and Measurement Technology Conference (I2MTC) Proceedings, Pisa, Italy, 11–14 May 2015. [CrossRef]
44. Carvalho, G.P.S.; Costa, R.R. Localization of an Autonomous Rail-Guided Robot Using Particle Filter. *IFAC-PapersOnLine* **2017**, *50*, 5642–5647. [CrossRef]
45. Kim, K.; Seol, S.; Kong, S.-H. High-speed train navigation system based on multi-sensor data fusion and map matching algorithm. *Int. J. Control Autom. Syst.* **2015**, *13*, 503–512. [CrossRef]
46. Rahimi, M.; Liu, H.; Cardenas, I.D.; Starr, A.; Hall, A.; Anderson, R. A Review on Technologies for Localisation and Navigation in Autonomous Railway Maintenance Systems. *Sensors* **2022**, *22*, 4185. [CrossRef] [PubMed]
47. Wang, Z.; Wu, Y.; Niu, Q. Multi-Sensor Fusion in Automated Driving: A Survey. *IEEE Access* **2019**, *8*, 2847–2868. [CrossRef]
48. Cao, Z.; Liu, J.; Jiang, W.; Cai, B.; Wang, J. INS/Odometer/Trackmap-aided Railway Train Localization under GNSS Jamming Conditions. In Proceedings of the Intelligent Vehicles Symposium (IV), Aachen, Germany, 4–9 June 2022. [CrossRef]
49. Specht, M.; Specht, C.; Stateczny, A.; Burdziakowski, P.; Dąbrowski, P.; Lewicka, O. Study on the Positioning Accuracy of the GNSS/INS System Supported by the RTK Receiver for Railway Measurements. *Energies* **2022**, *15*, 4094. [CrossRef]
50. Storck, C.R.; Duarte-Figueiredo, F. 5G V2X Ecosystem Providing Entertainment on Board Using Mm Wave Communications. In Proceedings of the 10th Latin-American Conference on Communications (LATINCOM), Guadalajara, Mexico, 14–16 November 2018. [CrossRef]
51. Meng, Y.; Feng, J.; Wang, W. An enhanced INS/GNSS integrated system with ODO for train positioning. In Proceedings of the 4th Advanced Information Management, Communicates, Electronic and Automation Control Conference (IMCEC), Chongqing, China, 18–20 June 2021. [CrossRef]
52. Legrand, C.; Beugin, J.; Conrard, B.; Marais, J.; Berbineau, M. Causal Analysis Methodology of Multisensor Systems based on GNSS. In Proceedings of the Second International Conference on Railway Technology: Research, Development and Maintenance, Ajaccio, France, 8–11 April 2014.
53. Salmi, P.; Torkkeli, M. Inventions Utilizing Satellite Navigation Systems in the Railway Industry—An Analysis of Patenting Activity. *J. Technol. Manag. Innov.* **2009**, *4*, 46–58. [CrossRef]
54. Simsky, A.; Wilms, F.; Franckart, J.-P. GNSS-based failsafe train positioning system for low-density traffic lines based on one-dimensional positioning algorithm. In Proceedings of the 2nd ESA Workshop on Satellite Navigation User Equipment Technologies NAVITEC '2004, Noordwijk, The Netherlands, 8–10 December 2004.
55. Scheier, B.; Bussmann, A.; Brinkmann, F.; Wendland, U. Cost efficiency analysis of the satellite based train control system 31nSat in Germany. *SIGNAL+DRAHT* **2015**, *11*, 36–40.
56. Gurník, P. Next Generation Train Control (NGTC): More Effective Railways through the Convergence of Main-line and Urban Train Control Systems. *Transp. Res. Procedia* **2016**, *14*, 1855–1864. [CrossRef]

57. Jakovljevic, M.; Geven, A.; Simanic-John, N.; Saatci, D.M. Next-Gen Train Control/Management (TCMS) Architectures: "Drive-By-Data" System Integration Approach. In Proceedings of the Embedded Real Time Software and Systems, Toulouse, France, 31 January–2 February 2018.
58. Haltuf, M. Shift2Rail JU from member state's point of view. *Transp. Res. Procedia* **2016**, *14*, 1819–1828. [CrossRef]
59. Wawrzyn, E. SHIFT2RAIL—Investments in innovations. *Sci. Res. Wars. Univ. Technol.* **2016**, *111*, 585–597.
60. Wawrzyn, E.; Stencel, G. Future Stations Solutions within IN2STEMPO Project of Shift2Rail. In Proceedings of the 24th International Scientific Conference "Transport Means—2020", Kaunas, Lithuania, 30 September–2 October 2020.
61. Goikoetxea, J.; de Eribe, D.O.; Grasso, A.; Bienfait, B. Shift2Rail TAURO: Technologies for the Autonomous Rail Operation. *Transp. Res. Procedia* **2023**, *72*, 3719–3722. [CrossRef]
62. Giuliano, R.; Mazzenga, F.; Vizzarri, A.; Vegni, A. Future Communication Systems for Railway: The AB4Rail project in H2020 Shift2Rail Programme. In Proceedings of the Transport Research Arena (TRA) Conference, Lisbona, Portugal, 15–18 April 2023. [CrossRef]
63. Damy, S. A Novel GNSS-Based Positioning System to Support Railway Operations. Ph.D. Thesis, Imperial College London, London, UK, 2016.
64. Hussain, A.; Ahmed, A.; Shah, M.A.; Katyara, S.; Staszewski, L.; Magsi, H. On Mitigating the Effects of Multipath on GNSS Using Environmental Context Detection. *Appl. Sci.* **2022**, *12*, 12389. [CrossRef]
65. Liu, J.; Cai, B.; Lu, D.; Wang, J. An Enhanced RAIM Method for Satellite-Based Positioning Using Track Constraint. *IEEE Access* **2019**, *7*, 54390–54409. [CrossRef]
66. Fikejz, J.; Kavicka, A. RegioRail—GNSS Train-Positioning System for Automatic Indications of Crisis Traffic Situations on Regional Rail Lines. *Appl. Sci.* **2022**, *12*, 5797. [CrossRef]
67. Major, F.G. *Quo Vadis: Evolution of Modern Navigation the Rise of Quantum Techniques*; Springer: Berlin/Heidelberg, Germany, 2014; pp. 311–366.
68. Liu, J.; Zhao, X.-L.; Cai, B.-G.; Wang, J. Pseudolite Constellation Optimization for Seamless Train Positioning in GNSS-Challenged Railway Stations. *IEEE Trans. Intell. Transp. Syst.* **2021**, *23*, 13636–13654. [CrossRef]
69. Department of Defense USA. Global Positioning System Standard Positioning Service Performance Standard. 2020. Available online: https://www.gps.gov (accessed on 2 March 2024).
70. Biradar, R.L. Architecture and Signal Structure of GLONASS. *Int. J. IT Eng.* **2015**, *3*, 94–106.
71. Filip, A.; Bażant, L.; Mocek, H.; Cach, J. GPS/GNSS Based Train Position Locator For Railway Signalling. *WIT Trans. Built Environ.* **2000**, *50*, 1227–1242. [CrossRef]
72. Zhu, G. Trajectory-Aided GNSS Land Navigation: Application to Train Positioning. Ph.D. Thesis, University of Technology of Troyes, Troyes, France, 2014.
73. Marais, J.; Meunier, B.; Berbineau, M. Evaluation of GPS availability for train positioning along a railway line. In Proceedings of the Vehicular Technology Conference Fall 2000, IEEE VTS Fall VTC2000, 52nd Vehicular Technology Conference, Boston, MA, USA, 24–28 September 2000. [CrossRef]
74. Januszewski, J. Satellite Navigation Systems in the Transport, Today and in the Future. *Arch. Transp.* **2010**, *22*, 175–187. [CrossRef]
75. Hensel, S.; Strauß, T.; Marinov, M. Eddy current sensor based velocity and distance estimation in rail vehicles. *IET Sci. Meas. Technol.* **2015**, *9*, 875–881. [CrossRef]
76. Kalašova, A.; Palička, L. Current State and Prospects of Satellite Navigation Applications in Transport. *Promet Traffic Transp.* **2007**, *19*, 121–128.
77. Schänzer, G.; Schneider, U.; Troelsen, J. The challenges of using satellite navigation systems for high precision railway positioning. *WIT Trans. Built Environ.* **2000**, *50*, 1281–1290. [CrossRef]
78. Rispoli, F.; Filip, A.; Castorina, M.; Di Mambro, G.; Neri, A.; Senesi, F. Recent progress in application of GNSS and advanced communications for railway signaling. In Proceedings of the 23rd International Conference Radioelektronika (RADIOELEKTRONIKA), Pardubice, Czech Republic, 16–17 April 2013. [CrossRef]
79. Chrzan, M.; Jackowski, S. *Współczesne Systemy Nawigacji w Transporcie Kolejowym*; Wydawnictwo UTH Radom: Radom, Warsaw, 2016.
80. Subirana, J.S.; Zornoza, J.J.; Hernández-Pajares, M. *GNSS Data Processing Volume I: Fundamentals and Algorithms*; European Space Agency: Noordwijk, The Netherlands, 2013.
81. Shi, C.; Wei, N. Satellite Navigation for Digital Earth. In *Manual of Digital Earth*; Springer Open: Beijing, China, 2019; pp. 125–160.
82. Januszewski, J. Modernization of Satellite Navigation Systems and Theirs New Maritime Applications. *TransNav Int. J. Mar. Navig. Saf. Sea Transp.* **2007**, *1*, 39–45.
83. Galileo GNSS. European GNSS (GALILEO)—Open Service—Service Definition Document. 2019. Available online: https://www.galileognss.eu (accessed on 5 March 2024).
84. Revnivykh, S.; Bolkunov, A.; Serdyukov, A.; Montenbruck, O. 8. GLONASS. In *Springer Handbook of Global Navigation Satellite Systems*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 219–243.

85. Karutin, S.; Testodov, N.; Tyulin, A.; Bolkunov, A. GLONASS. In *Position, Navigation, and Timing Technologies in the 21st Century: Integrated Satellite Navigation, Sensor Systems, and Civil Applications*; Springer: Berlin/Heidelberg, Germany, 2021; pp. 87–104.
86. Liu, J.; Cai, B.; Wang, J. An analysis of BeiDou Navigation Satellite System (BDS) based positioning for Train Collision Early Warning. In Proceedings of the IEEE Intelligent Vehicles Symposium (IV), Gold Coast, Australia, 23–26 June 2013. [CrossRef]
87. Yang, Y.; Mao, Y.; Sun, B. Basic performance and future developments of BeiDou global navigation satellite system. *Satell. Navig.* **2020**, *1*, 1–8. [CrossRef]
88. Yang, Y.; Tang, J.; Montenbruck, O. Chinese Navigation Satellite Systems. In *Springer Handbook of Global Navigation Satellite Systems*; Springer Handbooks; Springer: Berlin/Heidelberg, Germany, 2017; pp. 273–301.
89. Yang, C.H.; Zhang, Y.S. Research on the Architecture of Iot Middleware Platform Based on BeiDou Navigation Satellite System. In Proceedings of the 3rd International Conference on Mechatronics and Intelligent Robotics (ICMIR-2019), Kunming, China, 25–26 May 2019. [CrossRef]
90. Li, P.; Liu, Y.; Shao, S. System architecture and basic platform for intelligent high-speed railway. *Railw. Sci.* **2023**, *2*, 257–272. [CrossRef]
91. Han, C. The BeiDou navigation satellite system. In Proceedings of the IEEE XXXIth URSI General Assembly and Scientific Symposium (URSI GASS), Beijing, China, 16–23 August 2014. [CrossRef]
92. Kogure, S.; Ganeshan, A.; Montenbruck, O. 11. Regional Systems. In *Springer Handbook of Global Navigation Satellite Systems*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 305–338.
93. Kassem, M.M.; Raman, A.; Perino, D.; Sastry, N. A Browser-side View of Starlink Connectivity. In Proceedings of the IMC'22: Proceedings of the 22nd ACM Internet Measurement Conference, Nice, France, 25–27 October 2022. [CrossRef]
94. Michel, F.; Trevisan, M.; Giordano, D.; Bonaventure, O. A First Look at Starlink Performance. In Proceedings of the 22nd ACM Internet Measurement Conference, Nice, France, 25–27 October 2022. [CrossRef]
95. Freeman, R.H. Overview: Satellite Constellations. *J. Space Oper. Commun.* **2020**, *17*.
96. Mohan, N.; Ferguson, A.E.; Cech, H.; Bose, R.; Renatin, P.R.; Marina, M.K.; Ott, J. A Multifaceted Look at Starlink Performance. In Proceedings of the ACM Web Conference 2024 (WWW'24), Singapore, 13–17 May 2024; Association for Computing Machinery: New York, NY, USA; pp. 2723–2734. [CrossRef]
97. Spinsante, S.; Stallo, C. Hybridized-GNSS Approaches to Train Positioning: Challenges and Open Issues on Uncertainty. *Sensors* **2020**, *20*, 1885. [CrossRef]
98. Specht, M.; Szmagliński, J.; Specht, C.; Koc, W.; Wilk, A.; Czaplewski, K.; Karwowski, K.; Dąbrowski, P.S.; Chrostowski, P.; Grulkowski, S. Analysis of positioning methods using Global Navigation Satellite Systems (GNSS) in Polish State Railways (PKP). *Zesz. Nauk. Akad. Morskiej Szczecinie* **2020**, *62*, 26–35. [CrossRef]
99. Kochan, A. *Theoretical Foundations of the Digital Twin of ETCS Applications*; Politechnika Warszawska Oficyna Wydawnicza Politechniki Warszawskiej: Warszawa, Poland, 2023. (In Polish)
100. Beugin, J.; Legrand, C.; Marais, J.; Berbineau, M.; El-Koursi, E.-M. Safety Appraisal of GNSS-Based Localization Systems Used in Train Spacing Control. *IEEE Access* **2018**, *6*, 9898–9916. [CrossRef]
101. Crespillo, O.G.; Konovaltsev, A.; Marais, J.; Sabina, S.; Vennarini, A.; Coluccia, A.; Neri, A.; Aguila, A.; Razzano, E.; Ranauro, F.; et al. Local GNSS Threat Detection Methods for Virtual Balise Placement in Railway Applications. In Proceedings of the 16th International Conference on Intelligent Transportation Systems Telecommunications (ITST), Lisboa, Portugal, 15–17 October 2018. [CrossRef]
102. Toruń, A. *Research on the Impact of Wireless Data Transmission Technology on Positioning in Rail Transport*; Oficyna Wydawnicza Politechniki Warszawskiej: Warszawa, Poland, 2019. (In Polish)
103. He, Y.; Li, J.; Liu, J. Research on GNSS INS & GNSS/INS Integrated Navigation Method for Autonomous Vehicles: A Survey. *IEEE Access* **2023**, *11*, 79033–79055. [CrossRef]