The Galileo Positioning System: A Literature Review

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1. Introduction

1.1. Background on Global Navigation Satellite Systems (GNSS)

The term Global Navigation Satellite Systems (GNSS) refers to a satellite navigation system that intends to provide highly accurate longitudinal data, latitudinal data, altitudinal data, velocity and time data, and global coverage. Satellite navigation devices determine their location by using a time signal transmitted along a line of sight by radio from satellites. GNSS have become an indispensable part of modern life, enabling precise positioning, navigation, and timing (PNT) services across various applications—from transportation and telecommunications to agriculture, disaster management, and scientific research. The most well-known GNSS is the Global Positioning System (GPS) developed by the United States, followed by Russia's GLONASS, China's BeiDou, and the European Union's Galileo. The global coverage for each system is achieved by a satellite constellation of medium Earth orbit (MEO) satellites spread between several orbital planes.

1.2. Motivation and significance of Galileo

Galileo is a GNSS created by the European Union through the European Space Agency (ESA). It aims to provide high-precision positioning services independently to European political and military authorities, rather than relying on the US GPS or the Russian GLONASS systems, whose operators could potentially disable or degrade them at any time. Galileo represents a strategic effort to reduce dependency on non-European GNSS and enhance the performance, interoperability, and resilience of global positioning infrastructures. One of its key goals is to ensure high availability and accuracy for users worldwide, particularly in safety-critical and commercial applications. Galileo services are free and open to everyone. As part of the MEOSAR system, Galileo will also provide a new global search and rescue (SAR) function.

1.3. Scope and structure of the paper

This literature review aims to provide a comprehensive overview of the Galileo system. It will examine the system's development history, technical architecture, signal characteristics, and the services it offers. It will also consider the system's role within the broader GNSS ecosystem. Furthermore, it compares Galileo with other global systems, emphasising its distinctive features, innovations, and contributions. The paper is structured as follows: Section 2 provides a detailed overview of Galileo's design and architecture. Section 3 compares Galileo with other GNSS systems. Section 4 discusses its technical features. Section 5 explores the system's challenges and limitations. Section 6 reviews recent advancements and future directions. Section 7 presents the main conclusions.

2. Overview of the Galileo System

The Galileo satellite navigation system is a flagship project of the European Union, designed to provide a high-precision, independent service under civilian control. Unlike other GNSS systems, which originated for military purposes, Galileo aims to ensure reliability, accuracy, and accessibility for a wide range of civilian, governmental, and commercial users. This section explores the origins and evolution of the Galileo programme, its supporting technical infrastructure, and its key services.

2.1 Development History

Initial studies began in the late 1990s, and the Council of the European Union officially decided to proceed in 1999. The project was initiated and is funded jointly by the EU and the European Space Agency (ESA). The Galileo Joint Undertaking (GJU) was established in 2005 to oversee the development and validation phases. Oversight of the programme was taken over by the European GNSS Supervisory Authority (GSA), which the European Union Agency now replaces for the Space Programme (EUSPA). The technical design and infrastructure deployment were primarily carried out by the European Space Agency (ESA).

The first experimental satellite, GIOVE-A (the Galileo In-Orbit Validation Element), was launched on 28 December 2005, followed by a second test satellite, GIOVE-B, in April 2008. These missions were crucial in validating technologies and securing the radio frequency spectrum allocated to Galileo.

The first operational satellites were launched in 2011, marking the start of the In-Orbit Validation (IOV) phase. The Full Operational Capability (FOC) phase began in 2014, during which time the constellation was expanded through routine launches to reach its planned size of 30 satellites. On 15 December 2016, Galileo began providing its Initial Operational Capability (IOC). The services currently offered are the Open Service, the Public Regulated Service (PRS), and the Search and Rescue Service (SAR).

Despite facing several technical delays and political hurdles, Galileo has made steady progress and is now recognised as one of the most advanced GNSS systems. It offers remarkable accuracy, particularly in urban and multipath-prone environments.

2.2 Architecture and Infrastructure

The Galileo system is structured into three main segments: the space segment, the ground segment, and the user segment. Together, these components ensure the system’s global coverage, high-precision positioning capabilities, and reliable service. Figure 1 shows an overview of Galileo’s architecture.

Space Segment

The Galileo space segment comprises a constellation of 30 medium Earth orbit (MEO) satellites, of which 27 are operational and 3 are spares. Replacing any failed satellite within the same plane is made possible by the spares, thereby reducing the impact of failures on the quality of service. These satellites are distributed across three orbital planes at an altitude of approximately 23,600 kilometres with an inclination of 56 degrees. The orbit results in a repeated trace pattern concerning the Earth's orientation below them. This pattern repeats after ten days, during which each satellite completes seventeen revolutions. This configuration ensures optimal global coverage and allows for seamless integration with other GNSS constellations.

Each satellite is equipped with highly stable atomic clocks (hydrogen masers and rubidium clocks), precise Navigation and Search and Rescue payloads, and inter-satellite communication capabilities. The satellites transmit signals across multiple frequency bands, providing robustness against interference and multipath effects and enabling advanced services such as dual-frequency positioning and ionospheric error mitigation.

Ground Segment

The Galileo ground segment provides the control and monitoring infrastructure that ensures the system's orbit and signal accuracy. It includes:

- Two ground control centres are responsible for Satellite and Mission Control
- Seven telemetry, tracking & control (TT&C) stations
- Fifteen mission data Uplink Stations (ULS) that transmit updated navigation messages to the satellites.
- Several worldwide distributed reference sensor stations (GSS) that receive signals from the satellites for orbit determination and clock error correction.
- A data dissemination network between all geographically distributed locations
- One service centre to help Galileo users

The redundancy and distribution of these ground elements increase system resilience and continuity of service.

User Segment

The user segment consists of receivers and devices that collect the Galileo signals, determine pseudoranges (and other observables), and solve the navigation equations to obtain their coordinates and provide accurate time synchronization. This includes everything from smartphones and vehicle navigation units to professional-grade receivers for use in surveying, aviation, maritime applications, and timing. Galileo is designed to be interoperable with other GNSS systems, and modern receivers usually support multi-GNSS operation to improve positioning accuracy, availability, and reliability.

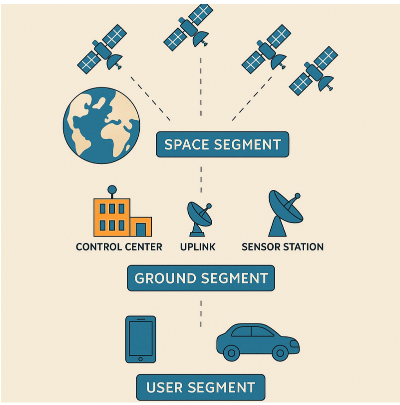

Fig. 1. Architecture and Infrastructure of Galileo

2.3 Objectives and Applications

The Galileo positioning system was developed with a set of clearly defined objectives that reflect the European Union's strategic priorities and practical needs. One of its primary objectives is to provide civilian-controlled navigation services that are independent of military-operated systems, such as the US GPS or Russian GLONASS systems. This strategic autonomy ensures that the EU retains full control over access to navigation services, which is particularly important in times of geopolitical tension or military conflict. The civilian nature of Galileo guarantees transparency, reliability, and continuity of service, free from military restrictions or priority access.

In addition to being independent, Galileo was designed to complement and enhance existing GNSS systems, providing high precision and global coverage. Its full interoperability with GPS and other GNSS systems improves performance, particularly in urban environments where satellite visibility may be limited. As discussed earlier, Galileo's dual-frequency capability further improves accuracy and integrity, making it ideal for safety-critical applications.

Galileo supports a wide array of applications across multiple sectors:

- Transportation: In aviation, Galileo supports precision approaches and landings. In maritime navigation, it improves route planning and collision avoidance. In road transport, it enables lane-level navigation, intelligent tolling systems, and fleet management. Railway systems also benefit from improved positioning for signalling and safety purposes.
- Telecommunications: Accurate timing signals from Galileo are essential for synchronising cellular networks, data centres, and broadcasting infrastructure.
- Agriculture: Precision farming applications, such as automated tractor guidance, planting, and harvesting, rely on GNSS to reduce resource waste.
- Science and Environment: Data from Galileo supports environmental monitoring, disaster management, earthquake research, and climate modelling.
- Emergency response: The Galileo Search and Rescue (SAR) service enables emergency beacons to be located more quickly. Users also receive a confirmation message once help is on the way, a unique feature of Galileo among GNSS systems.
- Consumer applications: Modern smartphones and wearable devices use Galileo to improve positioning, particularly when used alongside other GNSS constellations.

By pursuing these objectives and supporting diverse applications, Galileo reinforces Europe's technological sovereignty while delivering tangible benefits to citizens, industries, and governments.

3. Comparison with Other GNSS

As one of four major global navigation satellite systems (GNSS), Galileo is frequently compared to the GPS (United States), GLONASS (Russia), and BeiDou (China). While each system provides global coverage and positioning services, there are key differences in terms of control, performance, signal structure, and target users. This section outlines the key comparative attributes of Galileo and its alternatives.

3.1. Galileo vs. GPS

The Global Positioning System (GPS), developed and maintained by the United States Department of Defense, is the most widely used GNSS globally. It has been operational since the early 1990s and was originally intended for military use, though it later became available for civilian applications.

In contrast, Galileo was designed from the outset as a civilian-controlled system, managed by the European Union and the European Space Agency. This ensures continuous service availability without being subject to military control or limitations.

Key distinctions include:

- Signal Accuracy: Galileo provides higher positioning accuracy than GPS for civilian users, often reaching <1 meter, compared to GPS's typical accuracy of ~5 meters in standalone mode.

- Signal Availability: Galileo satellites transmit more complex signals (e.g., E5, E6 bands) and offer better performance in urban canyons and obstructed environments.
- Timing Precision: Galileo uses two main types of atomic clocks, passive hydrogen masers and rubidium atomic frequency standards (RAFS). This offers improved timing precision compared to GPS. Studies show that Galileo achieves an accuracy of 5 ns or less. At the same time, GPS typically has a timing precision of around 10 ns in the signal itself, and can degrade to 100 ns to 1 microsecond in most receivers.
- Search and Rescue (SAR): Galileo is part of the Cospas-Sarsat SAR system and uniquely includes a return link to notify users when their distress signal has been received—something GPS does not yet support.

3.2 Galileo vs. GLONASS and BeiDou

The Russian GLONASS system is comparable to GPS in architecture and global reach but generally offers slightly lower accuracy due to older technology and limited signal modernization. GLONASS satellites transmit signals on different frequencies, which can be beneficial in some conditions but complicate interoperability.

China's BeiDou system, completed in 2020, is the newest full GNSS. It offers advanced services including short messaging and precise point positioning, with a focus on regional dominance in Asia and growing international use.

Galileo stands out for:

- Transparency and data openness: Unlike GLONASS and BeiDou, which are state-controlled systems with military influence, Galileo offers free access to detailed documentation and performance reports.
- Service focus: Galileo aims at safety-critical applications and commercial innovation, offering services like the encrypted Public Regulated Service (PRS) and High Accuracy Service (HAS).

3.3 *Interoperability and Multi-GNSS Capabilities*

Galileo is explicitly designed to be interoperable with GPS, GLONASS, and BeiDou, meaning receivers can combine signals from different systems to enhance positioning performance.

- Advantages of multi-GNSS interoperability:
- Increased availability: More satellites in view lead to better coverage and faster acquisition.
- Improved accuracy and robustness: Cross-referencing signals helps reduce errors from ionospheric delays, clock drift, and multipath.
- Redundancy and resilience: Users are less affected by outages or degraded service in any single system.

Modern receivers, including smartphones, drones, and surveying instruments, often support multi-constellation GNSS, where Galileo plays a critical role in enhancing performance in both everyday and professional applications.

4. Technical Features and Innovations

4.1 The space segment

The Galileo space segment is designed to consist of 30 satellites. Of these, 27 will be active and 3 will be spares. They are deployed in the Medium Earth Orbit (MEO) at an altitude of 23,600 km. The satellites travel in three circular orbits with an inclination of 56 degrees to ensure global coverage. With a satellite orbital period of 14 hours, the constellation configuration guarantees at least six satellites in view at any time for any location, including the poles of the planet. Each satellite has an expected lifetime of 10 years. Individual satellites are replaced regularly to take into account any malfunctions, remaining lifetime, and adaptation to future payload technology.

4.2 The ground segment

The space segment is managed by two Control Centres located in Europe, which are supported by twenty Galileo Sensor Stations (GSS). The two Galileo Control Centres are located in Oberpfaffenhofen, Germany, and are mainly responsible for the control and management of the satellites (Satellite Control Center), and in Fucino, Italy, and are focused on the control of the mission and the management of the navigation services (Mission Control Center). Data exchanges between the Control Centres and the satellites are made via specific uplink stations. A total of 15 uplink stations have been installed around the world to facilitate this type of data transfer. As a main component of the ground segment, the Control Centres are responsible for the management of the satellites, the integrity of the signals, and the synchronization of the atomic clocks on the satellites.

4.3 Galileo signals and services

The Galileo system was designed to offer multiple high-quality signals, with an emphasis on interoperability and accuracy. The Galileo satellites transmit 10 different signals in the following main frequency bands. Specifically, the frequency bands it uses are E1 (1575.42 MHz), which is used by the Open Service (OS) and the PRS signal. Compatible with GPS L1. E5a (1176.45 MHz) and E5b (1207.14 MHz), which support the Commercial Service (CS), search and rescue (SAR), and offer higher accuracy. E6 (1278.75 MHz), which is intended for the Commercial Service and government and military services. The signal structure is based on Binary Offset Carrier (BOC) and AltBOC (for E5) technology, which allows increased immunity to interference and better separation between services. Specifically, BOC is a type of signal modulation developed to improve positioning accuracy, reduce interference between signals from different systems (e.g, GPS and Galileo), and allow better separation of signals on the same or similar frequencies. In BOC modulation, the signal carrier is offset and multiplied by a higher frequency square wave. This creates a double “hump” (two main peaks) in the signal spectrum instead of one, as is the case with classical techniques (e.g. BPSK). Alternative Binary Offset Carrier (AltBOC) is an improved and more complex version of BOC, designed specifically for Galileo, mainly for the E5 frequency band (1164–1215 MHz). The main characteristics of AltBOC are that it transmits two pairs of signals simultaneously (E5a and E5b), thus having the ability to simultaneously utilize two spectral regions, resulting in a greater range of information being sent. It provides a unified signal, integrating both frequencies. It is characterized by high positioning accuracy and stability, ideal for applications such as PPP. It also provides excellent multipath mitigation. These characteristics make Galileo particularly suitable for applications that require high performance and integrity. Galileo is designed to optimize position accuracy. In normal operation, the Open Service offers a horizontal accuracy of about 1 meter, with performance significantly improved through techniques such as Precise Point Positioning (PPP). According to studies, the Galileo signal-in-space range error (SISRE) is systematically lower than that of GPS during the period 2015–2018, ranging below 0.5 meters. The use of dual frequencies and a high-quality time reference reduces the influence of the ionosphere and other errors. Accurate time measurement is critical for GNSS. Galileo is based on an extremely accurate time scale, known as Galileo System Time (GST). The GST is synchronized with the International Atomic Time Scale (TAI) and is continuously monitored to maintain a deviation of less than 10 nanoseconds. Each satellite carries 4 atomic clocks: 2 hydrogen clocks (Passive Hydrogen Maser - PHM) and 2 rubidium clocks. The PHMs offer excellent stability, with long-term frequency stability better than 10^{-15}. The network of ground stations ensures the continuous updating and retransmission of time corrections. The GST synchronization accuracy directly contributes to the high positioning accuracy of the Galileo system and allows its use in demanding applications such as science, banking, finance, and telecommunications. The Galileo system offers, in addition to the basic navigation and timing capabilities, also integrity information of its signals, known as "integrity messages". These are mainly used in Search and Rescue (SAR) missions, but also in industrial applications where legal certification of location is required. Galileo's Open Service (OS) has better accuracy than GPS. The Commercial Service (CS) is offered for a fee and provides superior quality and reliability. The SAR service maintains the accuracy of the OS, but with enhanced integrity for critical applications. The Public Regulated Service (PRS) is encrypted and intended exclusively for government use. It is designed to maintain its operation even in crisis or attack situations, offering high resilience against spoofing and jamming. Its authorized users include EUROPOL, OLAF, civil protection services, security forces, and border control services. PRS is ideal for military and operational applications, as it ensures access when the rest of the Galileo services are not available.

5. Challenges, limitations, and delays in the development of the GALILEO system

The GALILEO GNSS system, despite the many years of development that preceded its implementation and construction, faced several significant problems during its implementation. The biggest problem it faced was the delays in terms of delivery dates. Initially, it was planned that the project would have been delivered complete and operational at the beginning of the previous decade. However, the system faced several problems that led to delays, such as the construction of the satellites, the sending of the satellites into space, and the construction and installation of all the ground equipment and facilities that the system needed to operate. Furthermore, technical problems such as the malfunction of the atomic clocks on some of the initial satellites and some incidents of cut-off or limitation of service provision, such as in July 2019, which lasted for days, further affected the delivery dates of the project, adding additional delays. All these problems also revealed several vulnerabilities in the system that needed to be fixed. Along with all these technical problems, several economic and political problems arose. As Galileo was and is one of the largest projects of the European Union, it faced several strict controls regarding its financing. The fact that it was developed and implemented during a period of economic crisis worldwide, and especially on the European continent, further increased the economic and political pressure that fell on the project. Furthermore, political disputes between the member states of the European Union caused several delays and difficulties due to the lack of decisions at critical periods for the project, resulting in the overall project going backwards. For example, the case of Brexit caused several problems in the project, as with the withdrawal of Great Britain from the European Union, several questions were raised about whether it could continue to participate in the development and implementation of this project. Despite the technical, economic, and political problems encountered by the GALILEO GNSS system, it managed to overcome them and become an important global tool integral to the global architecture of GNSS systems.

6. Recent Advances and Future Perspectives

As a dynamic and evolving system, Galileo continues to undergo significant advancements that enhance its capabilities, reach, and relevance in a rapidly digitizing world. From the deployment of next-generation satellites to the integration with cutting-edge technologies, Galileo is positioning itself at the forefront of global navigation innovation. This section explores recent upgrades, its synergy with emerging digital infrastructure, and its expanding role in critical autonomous and security-focused applications.

6.1 Upgrades and Next-Generation Satellites

The Galileo Second Generation (G2G) initiative represents a major step forward in the system's evolution. The European Space Agency (ESA) and the European Union Agency for the Space Programme (EUSPA) are jointly coordinating efforts to launch satellites that feature fully digital navigation payloads, electric propulsion, more powerful navigation antennas, inter-satellite links, and advanced atomic clock configurations, leading to a more robust and accurate system.

Key features of the G2G upgrade include:

- Fully Digital Navigation Payloads: These payloads offer greater flexibility and enable new navigation services.
- Electric Propulsion: Enables the satellites to move to their final operational orbits more efficiently and with greater precision.
- Enhanced Navigation Antennas: These antennas will have a more powerful signal, leading to improved signal quality and reception.
- Inter-Satellite Links: Allow satellites to communicate directly with each other, facilitating real-time coordination and potentially enhancing system robustness and accuracy.
- Advanced Atomic Clocks: The satellites will have more accurate onboard clocks, which are crucial for precise positioning and timing.
- Other Improvements: The G2 satellites will also include advanced jamming and spoofing protection mechanisms, further enhancing the system's security and reliability.

These upgrades are intended to ensure Galileo remains competitive and resilient in increasing GNSS demand and potential space-based threats.

6.2 Integration with Emerging Technologies

Galileo is increasingly integrated into emerging digital ecosystems, especially in the context of 5G networks and the Internet of Things (IoT). As 5G aims to connect billions of devices with ultra-low latency and precise timing, GNSS becomes essential for network synchronization, location-based services, and mobility management.

Key areas of integration include:

- Timing in 5G base stations: Galileo's highly accurate timing services help synchronize base stations, particularly in areas where terrestrial timing signals are unreliable.
- IoT localization: Galileo supports positioning for asset tracking, smart agriculture, and industrial automation, especially when combined with low-power wide-area network (LPWAN) technologies.

Moreover, the High Accuracy Service (HAS)—currently in pre-operational phase—will offer centimeter-level accuracy, enabling applications previously out of reach for mass-market users.

6.3 Role in Autonomous Systems and Security

The rise of autonomous technologies—such as drones, self-driving vehicles, and unmanned maritime systems—relies heavily on precise, secure, and continuous positioning. Galileo, with its advanced signal structure and open civilian governance, is well-suited to meet these demands.

Key roles in this area include:

- Automated driving: Galileo enhances lane-level accuracy, improving safety and efficiency in autonomous vehicles, especially in urban environments.
- UAV navigation: Drones benefit from Galileo's dual-frequency capabilities and improved accuracy for navigation, surveillance, and delivery missions.
- Public safety and defense: Galileo's Public Regulated Service (PRS) offers encrypted, anti-jamming positioning for government-authorized users in critical situations.
- Cybersecurity: As location data becomes a target for spoofing and interference, Galileo incorporates signal authentication features (OS-NMA: Open Service – Navigation Message Authentication) to verify integrity, particularly for critical applications.

These features collectively position Galileo as a key enabler in secure autonomous operations across domains such as mobility, defense, and infrastructure monitoring.

7. Conclusion

7.1 Summary

The Galileo Global Navigation Satellite System (GNSS) is a breakthrough in satellite navigation technology, distinguished by its sophisticated signal design, multi-frequency, and high-accuracy services. Galileo's signal scheme, particularly by the use of AltBOC modulation for the E5 band, offers better performance in terms of multipath mitigation and tracking robustness. The system yields centimeter order positioning accuracy with accurate point positioning and has a range of services from free open service to very accurate and encrypted commercial service. Galileo is also tightly synchronized to Coordinated Universal Time (UTC) by the extremely stable Galileo System Time (GST), supported by some of the world's top providers of space-based atomic clocks in orbit. Compatibility with other GNSS constellations also improves positioning performance, reliability, and robustness even more, and Galileo becomes an essential building block in several GNSS concepts of navigation. Galileo will provide very high accuracy to one meter for its commercial service, superior to that of GPS and GLONASS for civilian purposes. With the latest satellite navigation technology, Galileo offers services such as the Search and Rescue (SAR) service to aid worldwide security initiatives. GPS and GLONASS are of military origin and hence are not run by civilians, but Galileo is run and owned by civilians, whose operation has to align with civilian objectives without military constraints. Galileo aims to offer all-time coverage worldwide with a unique focus on Europe and offer worldwide reliable service. Although it is rapidly approaching full operational capacity, the Galileo system was never fully developed, limiting its coverage and performance in some areas. As the newest system, Galileo continues to prove its reliability and be integrated into global GNSS services, which may affect user adoption and device compatibility in the short term.

7.2 Importance of Galileo GNSS

The Galileo GNSS satellite navigation system is an important part of the global GNSS system space and a very useful tool worldwide. Its interoperability offers enormous benefits and possibilities while at the same time showing the example for future developments of new systems as well as upgrades of existing systems, demonstrating how a system controlled by a purely civilian staff can achieve and perform such results as well as how through the interoperability and cooperation of similar geo-location systems their overall performance can be optimized and the best possible service provision can be offered to the general public worldwide. Galileo, by emphasizing the provision of high-precision, secure, and attack-resistant services with global coverage, can support the ever-growing needs of modern applications that require the use of GNSS systems, such as self-driving cars, precision agriculture, aviation, navigation, and human security through the search and rescue program it offers. The ability to collaborate with similar systems significantly improves the coverage it has on the planet as well as the coverage it offers in specific areas, such as urban areas, but also areas with large obstacles, such as mountains and canyons, and thus ensures the best possible provision of services.

7.3 Future Outlook

In the future, it is expected that the GALILEO system will develop even further with various upgrades that are planned to be made such as the launch of a new generation of Galileo Second Generation (G2G) satellites where these satellites will offer even more advanced capabilities to the system such as advanced signal capabilities, higher power transmission and connections between satellites, capabilities are given that they will offer reduced latency and improve accuracy as well as achieve the best global range. Future upgrades of the system will further strengthen the authentication and cryptography used in the system to better address problems such as spoofing and jamming, making the system even more secure and stable against threats and attacks. With these energy sources, GALILEO is expected to be one of the best satellite fleets in the world and will ensure accuracy, security, availability, and interoperability to meet the most demanding needs worldwide for satellite navigation systems.

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