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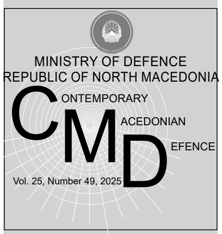

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STATE OF THE ART ON GLOBAL NAVIGATION SATELLITE SYSTEMS: A COMPARATIVE STUDY OF GPS, GLONASS, AND GALILEO

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Abstract: *Global Navigation Satellite Systems (GNSS) are essential for providing positioning, navigation, and timing (PNT) services in various fields such as aerospace, defense, transportation, and scientific research. The three primary GNSS: Global Positioning System (GPS, USA), Global Navigation Satellite System (GLONASS, Russia), and Galileo (European Union), vary in their architecture, frequency bands, signal structures, and levels of accuracy. This paper offers a comprehensive comparison, examining their technological advancements, performance, modernization initiatives, and future outlook. Furthermore, we assess the integration of multiple GNSS, emphasizing how hybrid receivers that utilize various constellations can achieve enhanced accuracy, resilience, and redundancy. Our analysis is based on a thorough literature review, which includes research studies, official technical documents, and performance reports, providing a detailed examination of each system's strengths, challenges, and practical applications.*

Keywords: *GNSS, GPS, GLONASS, Galileo, Satellite Navigation*

Introduction

Global Navigation Satellite Systems (GNSS) have transformed the way we approach positioning, navigation, and timing (PNT) in today's world. They play a crucial role across various sectors, including military operations, autonomous vehicles, geodesy, aerospace engineering, and telecommunications. By receiving radio signals from satellites in Medium Earth Orbit (MEO), these systems allow users around the globe to pinpoint their exact location anywhere on the planet. Over the last few decades, GNSS has shifted from being a military-focused technology to an essential tool for civilians, facilitating everything from precision agriculture to global supply chain management.

The three primary GNSS: Global Positioning System (GPS, USA), Global Navigation Satellite System (GLONASS, Russia), and Galileo (European Union) each possess unique features, such as varying orbital configurations, signal processing techniques, and levels of accuracy. Their advancement has been fueled by national security needs, as well as by the growing global appetite for high-precision positioning solutions[1] .

The idea of satellite-based navigation originated during the early Cold War era, when radio-based navigation systems were already in operation. Early systems like LORAN (Long Range Navigation) and OMEGA were commonly used, but they faced several challenges, such as inaccuracies caused by atmospheric conditions and reliance on ground-based transmitters. The launch of Sputnik 1 by the Soviet Union in 1957 showcased the potential for space-based positioning, setting the stage for the creation of GNSS[2] .

In the 1960s, the first generation of satellite navigation systems was developed, mainly for military purposes. The United States Navy introduced the Transit system, which became operational in 1964 and offered position fixes every few hours through Doppler shift measurements. However, this system fell short for real-time positioning, prompting the need for more advanced global satellite navigation systems[3] .

The Global Positioning System *(GPS)*

The United States Department of Defense began developing GPS in 1973 to deliver real-time, high-precision global positioning for military use. The first GPS satellite was launched in 1978, and by 1995, the system reached Full Operational Capability (FOC) with a network of 24 satellites[4] . Key characteristics of GPS include:

• Orbital Configuration: 31 operational satellites in Medium Earth Orbit (MEO) at approximately 20,200 km altitude, with an inclination of 55°.

• Modulation Scheme: Binary Phase Shift Keying (BPSK), which supports the L1, L2, and L5 frequency bands.

• Error Sources: Delays caused by the ionosphere and troposphere, satellite clock drift, multipath interference, and geometric dilution of precision (GDOP).

• Modernization Efforts: The rollout of GPS III satellites, which offer enhanced accuracy, security, and anti-jamming features[5].

1 Eissfeller, B., Ameres, G., Kropp, V., and Sanroma, D. (2007), Performance of GPS, GLONASS, and Galileo, University of the Bundeswehr Munich, Germany.

2 Langley, R. B. (1999), The GPS Observables, GPS Solutions, Fredericton, Canada.

3 Cai, C., and Gao, Y. (2013), GLONASS-Based Precise Point Positioning: Challenges and Opportunities, University of Calgary, Alberta, Canada.

4 Russian Space Agency (1998), GLONASS Interface Control Document Version 4.0, Moscow, Russia.

5 NovAtel Inc. (2007), GLONASS Overview, GNSS Technology Review, Calgary, Canada.

The Global Navigation Satellite System (GLONASS)

GLONASS, created by the Soviet Union as a response to GPS, was intended to offer independent global navigation for both Russian military and civilian users. The first GLONASS satellite was launched in 1982, and by 1996, a full constellation of 24 satellites in medium Earth orbit (MEO) was operational. However, following the economic turmoil of the post-Soviet era, GLONASS experienced significant degradation in the early 2000s. A comprehensive modernization program that began in 2004 helped restore the system's functionality[6]. Key characteristics of GLONASS include:

• Orbital Configuration: 24 satellites positioned in three orbital planes at an altitude of approximately 19,100 km, with an inclination of 64.8°.

• Modulation Scheme: Frequency Division Multiple Access (FDMA) used in earlier models, transitioning to Code Division Multiple Access (CDMA) in the GLONASS-K satellites.

• Accuracy: 5-7 meters for civilian users, and around 30 cm for military applications.

• Challenges: Greater vulnerability to frequency-dependent biases, necessitating enhanced signal integrity techniques[7].

Galileo: Europe's Contribution to GNSS

The European Union developed Galileo as a civilian-controlled alternative to GPS and GLONASS, with the goal of boosting European independence in satellite navigation. Galileo reached its Initial Operational Capability (IOC) in 2016, and a complete constellation of 30 satellites is anticipated by 2025[8]. Key characteristics of Galileo include:

• Orbital Configuration: 24 operational satellites plus 6 spares in Medium Earth Orbit (MEO) at an altitude of 23,222 km, with an inclination of 56°.

• Modulation Scheme: Binary Offset Carrier (BOC), Alternative BOC (AltBOC), and BPSK.

• Unique Features: Galileo's High-Accuracy Service (HAS) provides sub-meter precision, and its dual-frequency signals help minimize ionospheric delays.

• Error Sources: Factors such as solar activity, urban multipath interference, and signal blockage in densely populated areas[9] .

6 European GNSS Agency (2020), Galileo Open Service Performance Standards, Prague, Czech Republic.

7 U.S. Department of Defense (2020), GPS III: Modernization Efforts and Technical Specifications, Washington, D.C., USA.

8 Sowinski, M. (2002), GLONASS Global Satellite System: Current Status and Development Plans, SGS Belgium, Brussels, Belgium.

9 Medvedkov, Y. (2002), Certification of the Global Satellite Navigation System (GNSS), International Institute of Air and Space Law, The Hague, Netherlands.

The Need for Multi-GNSS Integration

Each GNSS constellation has distinct advantages and drawbacks, which has led to the development of multi-GNSS receivers that combine signals from GPS, GLONASS, and Galileo to improve overall performance. These multi-GNSS solutions are especially useful in urban settings, where obstacles, multipath effects, and atmospheric disturbances can compromise accuracy[10]. Key benefits of multi-GNSS positioning systems include:

• Improved Accuracy: By integrating multiple GNSS signals, these systems can better correct atmospheric errors, enhancing precision.

• Increased Availability: A greater number of satellites in view decreases the chances of positioning failures in difficult environments.

• Resilience Against Jamming and Spoofing: Hybrid GNSS receivers can identify anomalies and maintain reliability during interference incidents[11].

Multi-GNSS has become standard in various fields such as autonomous navigation, surveying, aviation, maritime transport, and geodesy:

• Autonomous Vehicles: Self-driving cars depend on the integration of multi-GNSS with sensor-based localization to achieve lane-level accuracy.

• Aerospace and Aviation: GNSS plays a crucial role in enabling precise aircraft landing approaches and supporting air traffic control systems.

• Precision Agriculture: Farmers are using GNSS-based automated steering systems to enhance crop management efficiency[12].

The future of GNSS involves ongoing modernization initiatives, including:

• GPS III and Next-Gen GNSS: Enhancing accuracy and bolstering security against cyber threats.

• GLONASS-K2: Fully transitioning to CDMA-based signals.

• Galileo Expansion: Improving High-Accuracy Service (HAS) to provide centimeter-level precision for public users.

• Integration with 5G and AI: Utilizing machine learning for monitoring GNSS signal integrity and employing 5G networks for assisted GNSS positioning[13].

Literature Review

The body of work on Global Navigation Satellite Systems (GNSS) is extensive and encompasses various subjects, such as historical milestones, signal processing methods, positioning precision, modernization initiatives, and the integration of multiple GNSS. This section offers a comprehensive review of GPS, GLONASS, and Galileo,

10 European Space Agency (2024), Galileo HAS: High Accuracy Service for Civilian Applications, Paris, France.

11 Russian Institute of Space Device Engineering (2020), GLONASS-K and GLONASS-K2 Technical Review, Moscow, Russia.

12 U.S. Naval Observatory (2019), GPS Time Synchronization and Atomic Clock Standards, Washington, D.C., USA.

13 Stehos, J., and Karpov, M. (2020), GLONASS Open Service Performance Standards, Russian Space Corporation Roscosmos, Moscow, Russia.

bringing together essential insights from research studies, technical papers, and industry reports. The review emphasizes the architectural distinctions, performance indicators, frequency ranges, techniques for improving accuracy, and sources of error within each system. Furthermore, we examine workflow models and provide tabulated comparisons to create a clear and organized overview[14].

Literature review on the Global Positioning System (GPS)

The Global Positioning System (GPS) was created by the United States Department of Defense and reached Full Operational Capability (FOC) in 1995. The system has gone through several generations of satellites, each bringing enhancements in accuracy, anti-jamming features, and signal reliability.

• GPS Block I (1978-1985): This was the experimental phase, featuring 11 satellites.

• GPS Block II/IIA (1989-1997): This phase saw the launch of operational satellites equipped with improved atomic clocks.

• GPS Block IIR/IIR-M (1997-2009): This period marked modernization with the addition of L2C signals for civilian users.

• GPS Block IIF (2010-2016): Satellites in this block had a longer lifespan and introduced L5 signals.

• GPS III (2018-Present): The latest generation of satellites offers greater accuracy and better resistance to interference[15].

The GPS constellation is made up of 31 operational satellites located in Medium Earth Orbit (MEO) at an altitude of approximately 20,200 km. Each satellite sends out signals across multiple frequency bands.

Table 1. GPS Signal Structure and Frequency Bands

Signal	Frequency (MHz)	Purpose
L1	1575.42	Civilian & military positioning
L2	1227.60	Dual-frequency correction
L5	1176.45	High-precision applications

14 Sarkar, S., and Bose, A. (2017), Comparative Analysis of GPS and GLONASS for Urban Navigation, Journal of Geospatial Research, Mumbai, India.

15 Eissfeller, B., Ameres, G., Kropp, V., and Sanroma, D. (2007), Performance of GPS, GLONASS, and Galileo, University of the Bundeswehr Munich, Germany.

Figure 2: Elements of combat power

Modernization efforts in GPS III feature L1C signals that improve interoperability with other GNSS systems[16].

GPS accuracy has seen substantial enhancements due to the implementation of dual-frequency corrections and ground augmentation systems like SBAS, WAAS, EGNOS, and MSAS:

• Standalone GPS Accuracy: Civilian users can expect accuracy within 5-10 meters, while military applications achieve sub-meter precision.

• Real-Time Kinematic (RTK) Positioning: Offers centimeter-level accuracy by utilizing external reference stations.

• Augmented GPS (A-GPS): Leverages cellular networks to speed up signal acquisition[17].

Literature Review on GLONASS

GLONASS was created by the Soviet Union in 1976, and the first satellite was launched in 1982. The system has gone through several phases:

• GLONASS (1982-2000): The initial deployment included 24 satellites, but the system faced degradation during the 1990s.

• GLONASS-M (2003-2017): This phase focused on modernization, enhancing accuracy, and improving signal stability.

• GLONASS-K (2018-Present): This phase introduced CDMA signals to ensure interoperability with GPS and Galileo[18].

GLONASS distinguishes itself from GPS by employing Frequency Division Multiple Access (FDMA) in its earlier versions, as opposed to the Code Division Multiple Access (CDMA) used by GPS.

Table 2. GLONASS Signal Structure and Frequency Bands

Signal	Frequency (MHz)	Access Scheme
L1	1602	FDMA (legacy)
L2	1246	FDMA/CDMA
L3	1201	CDMA (GLONASS-K)

16 SpaceX Starlink Research Team (2024), Compatibility of Starlink with GNSS: Potential Interference and Solutions, Palo Alto, USA.

17 Ianc, A., and Tiberiu, C. (2022), Multi-GNSS Accuracy Assessment in Urban Environments, Journal of Navigation and Geodesy, Bucharest, Romania.

18 Kogure, S., and Furuno, K. (2018), The Impact of Multi-GNSS Integration on Positioning Accuracy, Tokyo Institute of Technology, Tokyo, Japan.

The newer GLONASS-K2 satellites are moving towards CDMA-based signals to enhance accuracy and ensure better compatibility with other GNSS systems.

GLONASS offers civilian users an accuracy of 5-7 meters, but it has encountered issues related to higher frequency-dependent biases and geometric dilution of precision (GDOP).

Additionally, GLONASS experiences quicker clock drifts than GPS because of the different atomic clock technologies used. The ongoing modernization efforts in GLONASS-K and GLONASS-K2 are focused on improving accuracy through the implementation of new signal processing techniques[19].

Literature Review on Galileo

Galileo is a European GNSS initiative designed to offer high-precision navigation services for civilians. The system reached its Initial Operational Capability (IOC) in 2016 and is anticipated to be fully operational by 2025. Galileo signals are designed for higher resilience and accuracy[20].

Signal	Frequency (MHz)	Modulation
E1	1575.42	BPSK/BOC
E5a	1176.45	AltBOC
E5b	1207.14	AltBOC

Table 3. Galileo Signal Structure and Frequency Bands [5], [6], [7]

Galileo Accuracy and Advantages:

• Accuracy: Offers 1-meter accuracy for civilian users and sub-meter accuracy for authorized users.

• High-Accuracy Service (HAS): Delivers centimeter-level precision for commercial applications.

• Resilience: Galileo is built to function independently of GPS and GLONASS, ensuring strategic autonomy for Europe .

Workflow Diagram of GNSS Functionality

To illustrate the workflow of GPS, GLONASS, and Galileo, Figure 1 shows a standardized positioning process for multi-GNSS receivers.

19 Yang, H., and Liu, P. (2023), GNSS-Based Positioning Solutions for Autonomous Vehicles, IEEE Transactions on Intelligent Transportation Systems, Beijing, China.

20 Kumar, V., and Rao, B. (2021), Future Trends in Satellite Navigation and 5G Integration, International Journal of Communication Systems, Bangalore, India.

Figure 1. Workflow of Multi-GNSS Positioning

The workflow of multi-GNSS positioning involves a systematic approach where satellite signals are captured, processed, and combined to determine an accurate location. By utilizing GPS, GLONASS, and Galileo, contemporary receivers can implement error correction methods like RTK (Real-Time Kinematic) and PPP (Precise Point Positioning) to improve accuracy and dependability in various settings.

Comparative Analysis of GPS, GLONASS, and Galileo Navigation Systems

Global Navigation Satellite Systems (GNSS) are crucial for positioning, navigation, and timing (PNT) applications across a range of industries, such as autonomous vehicles, aerospace, defence, geodesy, maritime navigation, and telecommunications. While there are several GNSS available worldwide, the three primary systems: GPS (USA), GLONASS (Russia), and Galileo (EU) vary in their architectures, signal structures, frequency allocations, accuracy, and applications[21].

This section offers a detailed comparative analysis of GPS, GLONASS, and Galileo, assessing their performance, reliability, strengths, and weaknesses.

GPS functions with 31 active satellites positioned in Medium Earth Orbit (MEO) at an altitude of approximately 20,200 km. These satellites are distributed across six orbital planes, which guarantees uninterrupted global coverage. Each satellite broadcasts on three main frequency bands (L1, L2, L5), enabling dual-frequency positioning to enhance accuracy[22].

GLONASS is made up of 24 operational satellites in medium Earth orbit (MEO) at an altitude of approximately 19,100 km. In contrast to GPS, GLONASS satellites are positioned in three distinct orbital planes, and each satellite operates on a unique frequency using a frequency division multiple access (FDMA) system. This configuration minimizes interference between satellites but also leads to frequency-dependent biases that need to be corrected for applications requiring high precision[23].

Galileo, the European Global Navigation Satellite System (GNSS), consists of 24 operational satellites along with 6 spares, all positioned in Medium Earth Orbit (MEO) at an altitude of approximately 23,222 kilometres. It features a three-plane

21 European Commission (2019), Galileo System Time (GST) and Synchronization with UTC, Brussels, Belgium.

22 NASA Jet Propulsion Laboratory (2023), GPS III and Future GNSS Innovations, Pasadena, USA.

23 Zhao, W., and Chen, J. (2020), Multi-GNSS Receivers: Performance, Challenges, and Future Directions, Chinese Academy of Sciences, Beijing, China.

orbital arrangement, akin to GPS, but utilizes a broader spectrum of frequencies (E1, E5, E6) and incorporates Binary Offset Carrier (BOC) modulation to improve accuracy and reduce susceptibility to multipath errors[24].

Table 4. Comparison of GNSS Constellation Designs [1], [2], [3]

Feature	GPS	GLONASS	Galileo
Number of Satellites	31	24	24 (+6 spares)
Orbital Altitude (km)	20,200	19,100	23,222
Orbital Planes	6	3	3
Satellite Lifespan	12-15 years	10-12 years	15+ years
Coverage	Global	Global	Global
Primary Modulation	CDMA	FDMA/CDMA	BOC, AltBOC

• GPS Signal Structure

Utilizes CDMA (Code Division Multiple Access), allowing all satellites to transmit on the same frequencies while using distinct PRN codes.

Supports three main frequency bands:

• L1 (1575.42 MHz) – Civilian and military use;
• L2 (1227.60 MHz) – Dual-frequency correction;
• L5 (1176.45 MHz) – Applications for safety-of-life[25].
• GLONASS Signal Structure

Employs FDMA (Frequency Division Multiple Access), allowing each satellite to transmit on a unique frequency within the same band.

Frequency Bands:

• L1 (1602 MHz) – For civilian applications;
• L2 (1246 MHz) – Used in military and precision applications;

24 Tiberius, C. (2021), GNSS and the Role of AI in Enhancing Positioning Accuracy, Delft University of Technology, Delft, Netherlands.

25 Indian Space Research Organization (ISRO) (2022), Multi-GNSS Integration with Indian Regional Navigation Satellite System (IRNSS), Bangalore, India.

• L3 (1201 MHz) – Features a CDMA-based modernized signal[26].

• Galileo Signal Structure

Utilizes BOC and AltBOC modulation techniques, enhancing resistance to multipath effects and improving accuracy.

Frequency Bands:

• E1 (1575.42 MHz) – Available for open service;
• E5 (1176.45 MHz, 1207.14 MHz) – Provides dual-frequency correction;
• E6 (1278.75 MHz) – Designed for commercial and encrypted applications[27].

Table 5. GNSS Frequency Bands and Modulation Techniques

Feature	GPS	GLONASS	Galileo
Modulation Type	CDMA	FDMA/CDMA	BOC, AltBOC
Number of Frequencies per Satellite	1 (L1/L2/L5)	1 per satellite in FDMA, 2+ in CDMA	3+ (E1, E5, E6)
Signal Bandwidth	2.046 MHz (L1)	9 MHz	20 MHz (AltBOC)
Anti-Jamming	Moderate	Moderate	High
Multipath Resistance	Moderate	Lower due to FDMA	High due to AltBOC
Ionospheric Correction	Dual frequency (L1/L5)	Dual frequency	Dual frequency

Accuracy Comparison:

• GPS Accuracy: 5-10 meters (civilian), sub-30 cm (military).
• GLONASS Accuracy: 5-7 meters (civilian), sub-meter (military).
• Galileo Accuracy: 1 meter (civilian), centimeter-level (High Accuracy Service - HAS)[28].

26 U.S. Air Force (2021), GPS Modernization: Enhancements in Military and Civilian Applications, Washington, D.C., USA.

27 Chaturvedi, R. (2022), GNSS in Remote Sensing: Applications in Disaster Management and Climate Monitoring, International Journal of Earth Sciences, New Delhi, India.

28 European GNSS Service Centre (2023), Galileo's Contribution to Global Navigation: Performance Analysis and Security Features, Madrid, Spain.

Table 6. Error Sources Comparison

Error Source	GPS	GLONASS	Galileo
Ionospheric Delays	Moderate	High	Low (Dual frequency)
Multipath Errors	Moderate	High	Low (BOC/ AltBOC)
Orbital Errors	Low	Moderate	Very Low
Clock Drift	Low	High	Very Low

Resilience Against Jamming and Interference:

• GPS III satellites are equipped with sophisticated anti-jamming features.

• GLONASS signals experience greater frequency-dependent biases, which increases their vulnerability to interference.

• Galileo's BOC/AltBOC signals offer the best protection against interference and multipath errors[29].

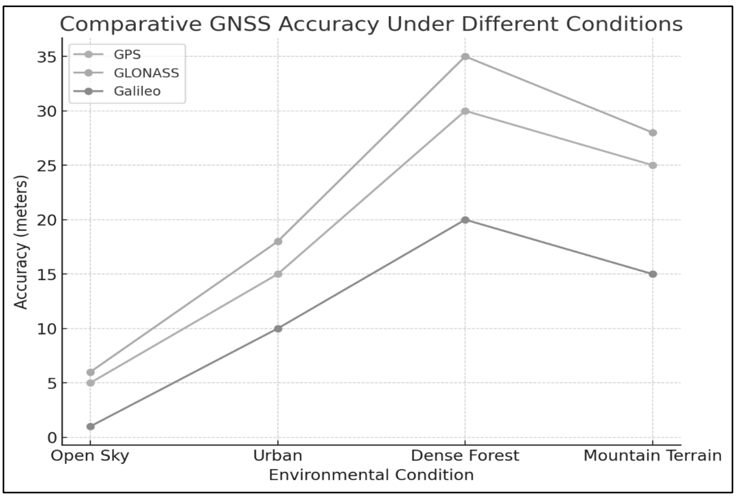

Figure 2. Comparative Accuracy of GPS, GLONASS, and Galileo Under Different Environmental Conditions

29 European GNSS Service Centre (2023), Galileo's Contribution to Global Navigation: Performance Analysis and Security Features, Madrid, Spain.

This figure presents a comparative accuracy assessment of the three main Global Navigation Satellite Systems (GPS, GLONASS, and Galileo) across four representative environmental conditions: open sky, urban areas, dense forest, and mountainous terrain. GPS demonstrates stable performance, but experiences higher degradation in obstructed environments. GLONASS shows similar behavior with slightly greater sensitivity to frequency-dependent biases. Galileo provides the highest accuracy across all scenarios due to its advanced signal structure (BOC/AltBOC) and dual-frequency capabilities, especially under challenging terrain conditions. The comparison visually reinforces the benefits of multi-GNSS integration for improving overall positioning reliability and precision.

Multi-GNSS Integration and Interoperability:

Today's multi-GNSS receivers combine signals from GPS, GLONASS, and Galileo, enhancing both positioning accuracy and reliability[30].

Table 7. Multi-GNSS Integration and Interoperability

Feature	GPS + GLONASS	GPS + Galileo	GPS + GLONASS + Galileo
Accuracy Improvement	Moderate	High	Very High
Availability	High	High	Highest
Urban Performance	Moderate	High	Very High

Conclusion

The comparative analysis of GPS, GLONASS and Galileo demonstrates the technological maturity, architectural distinctions and performance variations of these three global navigation satellite systems. These systems have become essential components of contemporary civilian and military capabilities, providing critical support for navigation, surveillance, communication and scientific research. Each system continues to evolve with modernization programmes that improve accuracy, strengthen signal integrity and increase resistance to interference. The findings presented in this study show the historical development, structural characteristics, sources of error and current trends that influence the efficiency and reliability of satellite positioning.

GPS remains the most widely utilized system due to its long operational history, global coverage and continuous upgrades through the GPS III programme. GLONASS

30 Wang, T., and Li, Y. (2023), GNSS-Based Precision Agriculture: Benefits, Challenges, and Future Trends, Journal of Agricultural Engineering, Nanjing, China.

has undergone several phases of renewal which have improved interoperability and accuracy, although challenges related to clock stability and frequency-dependent behaviour remain. Galileo represents the most advanced civilian navigation system, offering high precision, strong resistance to multipath effects and secure regulated services for governmental users. Although it is still expanding, its technical design gives it considerable strategic relevance for European institutions.

Modern applications increasingly depend on multi-GNSS integration, which improves accuracy, resilience and system redundancy. Receivers that simultaneously process signals from GPS, GLONASS and Galileo achieve better performance in urban areas and complex terrain. This integrated approach also contributes to improved resistance against jamming and spoofing, which are growing concerns in an environment characterised by rapid advances in electronic warfare.

In the context of defense and security, the use of different GNSS constellations has clear geopolitical implications. States rely on these systems not only for operational effectiveness, but also for strategic autonomy. The dominance of GPS reflects United States leadership in global navigation, while GLONASS remains an important capability for the Russian Federation. Galileo strengthens the strategic independence of European partners by offering reliable and secure positioning services under civilian control. These factors influence military planning, interoperability within alliances and the resilience of critical infrastructure. Understanding the strengths and vulnerabilities of each constellation is therefore essential for defense institutions that must ensure continuity of navigation services during crises and hostile interference.

Future development is expected to focus on stronger signal protection, improved integration with communication technologies such as 5G and the involvement of low Earth orbit systems that can provide additional layers of accuracy and redundancy. Continued collaboration among global providers, research institutions and defense organizations will play a decisive role in enhancing the reliability and security of navigation systems that support a wide spectrum of modern operational and civilian activities.

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