Readiness of Galileo PNT Service for NATO Operations Threats and Challenges

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Abstracts: In the domain of the Defense ICT-based technology: (Information and Communication Technology), most of the worldwide defense operations, including the North Atlantic Treaty Organization (NATO) operations, are significantly relying on the space support services. One of the most essential services is the Positioning, Navigation and Timing (PNT) service, which is currently provided by the United States' Global Positioning System (GPS). The GPS has become a global utility comparable to the internet, and it does not 'just' provide positioning data, but also provides the most important civilian/military use of the timing signal, which synchronizes all the communication and the encryption in all operations. While the USA has formulated first requirements to strengthen the resiliency of GPS in terms of the availability of accuracy, the availability of integrity and the availability of continuity, NATO has additional options to improve resiliency by integrating the European Galileo constellation. This paper focus mainly on the military implications of these two Global Navigation Satellite Systems (GNSS), to order to enrich the knowledge of the NATO members and policymakers about the PNT options available to the alliance, as well as addressing the various threats and challenges facing the PNT services.

Keywords: Galileo, GPS, PNT, NATO, GNSS, ICT.

1. INTRODUCTION

The importance of this study embedded in the fact that the space domain has recently and hugely become the fourth operational theater of technological race, alongside with the sea, the land and the air theaters. The space-based technologies are so essential not only for military purposes, but also for the civilian huge usage, both in all domains. The usage of the space-based technology has been hugely involved in all aspects such as: communications, navigation, surveillance, cell phones, and many military/civilian activities. Most importantly for this chapter; the space ICT-based technologies has been emerged as the top priority on the NATO agenda. Within the adoption of a space policy and the declaration of space as an operational NATO domain, the alliance has recognized the need to adapt to this rapidly evolving challenge. Moreover, the creation of a NATO Space Centre at Allied Air Command in Ramstein, Germany, as well as the creation of the Centre of Excellence (CoE) in Toulouse, France are the significant first steps in response to these challenges, as per reported by the NATO Secretary General Jens Stoltenberg, (BRUNNER, 2021). Based on fact that the new Galileo GNSS system will become into the full service in the near future, the need to adapt a NATO space policy for alliance is becoming more demanding and crucial, it would not be only beneficial for enhancing the performance of operations, but it is also crucial to be interoperable with others in the same time, place and mission. As it can be quoted by the Secretary General of NATO when he said: "What happens in space is of great importance for what we can do on the Earth".

As a result of this adoption, NATO has to cop up with the new GNSS satellite-based technology by pursuing its real implementations in all aspects. Furthermore, the new polices and strategies have to be based on the technical knowledge behind the different options of the GNSS systems, particularly, the new European Galileo system. The new Galileo system went through a long way of both approvals and developments till it has recently seen the light in the common space, besides the other GNSS systems. Galileo has been recently operating as initial capability consisting of 27 satellites in a global coverage, and it still needs three more satellites to complete its full constellation, at which it can be considered as a system of Full Operational Capability FOC. Therefore, the main purpose of this study is focusing on optimizing the usage of the main two systems only, the currently US GPS system and the foreseen European Galileo system, and how would be the actions of the transition period from the first system to the second one look like.

In fact, the satellite-based technology is very huge, it contains the three main pillars within the CNS concept: Communication, Navigation and Surveillance. Therefore, the scope of the study is shortened to the Navigation aspect only, Excluding the Communication and Surveillance aspect from this study is a significant consideration in order to pipe the research to the Navigation aviation domain that suits the title of the study, this consideration doesn't mean they are not important for NATO, but more irrelevant. The global coverage in navigation competition with the other GNSS systems such as: the US GPS system, the Russian GLONASS system and the newly-completed Chinese Beidou system is very critical in time, cost and quality of service, and the Navigation WARFARE (NAVWAR) is dramatically expediting year after year. Actually, the above four systems are the only systems which provides the global navigation satellite services GNSS, they are funded and operated by the superior global powers in the world, USA, Russia, Chinese and Europe (represented by EU and NATO). The other remaining systems are just Regional Navigational Satellites Services (RNSS), such as the Japanese system: Quasi-Zenith Satellite System – QZSS, and the Indian system: Navigation with Indian Constellation NavIC, but both are aiming to global extension. However, both QZSS and NavIC won't be discussed in this chapter due to their regional coverage and not global. On the other hand, all the augmentation systems which are depending on augmentation of the original GNSS signal won't be discussed within the scope of this chapter also, because their availability is dependent on the GNSS itself, once it is not there, they become useless. In addition, referring to the main four GNSS systems, the only two that were discussed in this article are GPS and Galileo, the reason behind excluding the Russian GLONASS system is due to different frequency plan used in the common service, and the excluding of the Chinese Beidou system is due to its newly converted to GNSS system but not FOC yet, its signal in space is not checked for global stability purpose yet, it was used as RNSS system regional over China and the far east space only for long years before 2021. Furthermore; since the ground stations in China cannot continuously track and control all Beidou satellites — the system lacks a fully global ground control network — the inter-satellite links help establish communication among them. Instructions sent by the control center to one satellite in the constellation are transmitted to all. This technique had been started since 2016 and it is still under testing. (insidegnss-Beidou, 2020).

In this paper, the matter subject is divided in the following areas, each in a separate section: (1) historical background of Galileo, (2) technical background of Galileo w.r.t GPS, (3) challenges and threats, (4) conclusions. The chapter also contains some figures and facts of the new statics that show the percentages of transition to space technology worldwide. All are referenced to official sites and reports recently issued. By completion of the paper, conclusions would be good guidance in the way of the adoption and the transition to space-based technology, particularly, the Galileo provided services in the near future.

2. HISTORICAL BACKGROUND OF GALILEO

As mentioned in the introduction, the four Global GNSS systems are now growing in a dramatically speed to the space, see Fig. 1 below. Therefore, the four GNSS – GPS (USA), GLONASS (RU), Beidou (PRC) and Galileo (EU) – will continue to provide navigation services with global coverage for the foreseeable future, with more than 100 GNSS satellites in Medium Earth Orbit (MEO). BeiDou-3 satellites have been launched at an impressive rate during 2018-2019, and Galileo 'Batch 3' satellites are due to follow suit from 2021 to complete and maintain the constellation. The three Regional Navigation Satellite Systems (RNSS), namely the Indian NavIC, the Chinese Beidou (phase 2, formerly known as Compass) and Japanese QZSS further increase the number of navigation satellites in their respective coverage areas. The Satellite-Based Augmentation Systems (SBAS), such as the European Geostationary Navigation Overlay System (EGNOS), broadcast GNSS-like signals primarily dedicated to the provision of integrity information and wide area corrections but can also be used as extra navigation signals.

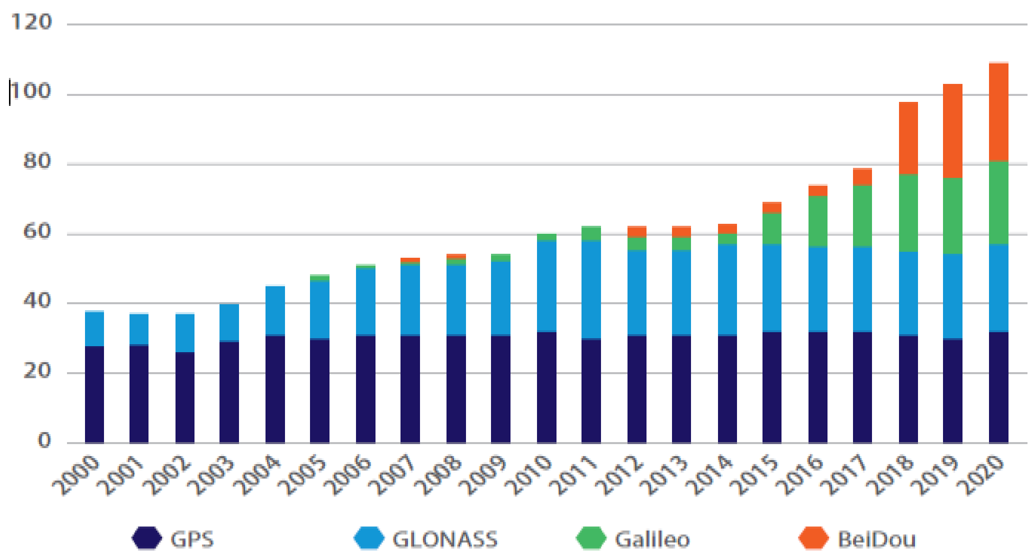

Figure 1: Operational GNSS Satellites in the MEO excluding the test satellites (Costa, 2020).

Up to now, the main two GNSS systems that would be under scope for NATO Adoption are: the currently GPS system and the expected Galileo system, both of them would be the best choice of approach in terms of a permanent and a dependent systems in order to correctly fulfil the operational needs. Neither the other GNSS systems nor the augmentation systems would optimize the technical PNT solutions for the NATO adoption of the space-based technologies. But the transition to European Galileo system from the US GPS system would be considered the most significant milestone in the way of conversion. From this point, the question raised how Europe could have Galileo footprint in space? What is struggle they had been through, politically and technically, until they have successfully achieved Galileo signal in space? This is the main objective of this section.

First of all, the idea behind having Galileo system in space while the GPS is there and operating well for NATO allies was refused by the United States (US). It was in their point of view a wasting of money, effort and time. But the European Union (EU) had seen Galileo of a great importance as a sort of independency: politically, economically, and technically. In addition, from security perspective, EU debated their security threats in all other aspects that depending on PNT services such as banks and big data synchronization while relying on non-own GPS system. Also, the GPS signal would be more accurate and steady available when combined with Galileo signals. Therefore, and based on the mentioned debates, the long way of challenges to EU had started, both technically, financially and approvals in space usage. This long way of process is published in (Ahmad, 2019) with full details, but it can be summarized in the following paragraphs shortly.

Firstly, and in terms of the improved performance, the Europeans' basic assumption was that the GPS system may not be upgraded to meet the future needs; their debates were that the enhanced GPS B-III was planned to begin launching in 2012 (Beidleman, 2006), but unfortunately, it is currently anticipated to be launched in 2022 or may be beyond (GPS, 2006). Hence, the GPS current performance in the form of accuracy, reliability and vulnerability became a primary concern and a strong motive for the European development of Galileo. Furthermore, the GPS accuracy still degrades at high latitudes and in urban areas; the five-meter accuracy of GPS is available only 17% of the time, also the GPS civilian service (SPS) cannot be guaranteed worldwide all the times. For example, in 2000, GPS satellite malfunctions deprived the areas of Oklahoma, Kansas and Nebraska from navigational signals for 18 minutes. Consequently, if the satellite navigation is considered a keystone of transportation infrastructure, then even minor service discontinuities would cause severe consequences on the safety of people and assets. Based on that, Galileo is foreseen to be the promising global navigational satellite system, which will overcome all these deficiencies and GPS Block III will also overcome most of them and free of charge to the users (Binary Offset Carrier (BOC) and Binary Phase Shift Keying (BPSK) Modulation in indoor Drones GNSS Recievers using Multipath Error Envelope MEE Technique, 2023).

Furthermore, and in terms of GNSS importance, it has obviously been noted that no single NATO mission had been performed without using the current GPS systems; it is being used in every single air force, land and Maritime's missions. Therefore, the GPS system has been the essence and the core of many operational needs since its announcement date, such as: the digital mapping, the unified timing and the common synchronizations especially in the deployable operations. Furthermore, and from a military perspective, signal officers on duty whilst the planning phase of operation should investigate the applicable technologies and the possible technical devices in order to give the needed suggestions for the implementation. Moreover, the digital soldier must nowadays be the best-equipped soldier of the battlefield who is connected to the theatre of war/ operations with all it is needed of the latest technologies such as computers, wireless communication and by using GPS receivers. Therefore, the personal communication system should provide the ability to perform all the tasks with the appropriate support such as the digital GPS maps, the picture and voice commands and the messaging options (Hronyecz, 2015). Hence, it is important in place, that the EU operational decision-makers to seek for the optimal best technologies that meet their missions accomplished precisely and successfully, depending on their own secure timing and synchronization of the potential Galileo system.

However, it was definitely clear for the EU that they can successfully proceed in their own Research and Development R&D efforts. Moreover, and according to NATO and EU, a newly owned GNSS system with an improved technical performance higher than the given GPS SPS services by USA to NATO allies in joint Operations, is strongly needed.

Secondly, and in terms of the independence from the United States, the rationale behind it was identified as follows:

The political independence: Europe plans to employ a GNSS to aid the implementation of a broad set of policies that includes regulating agriculture, fisheries and transportation services. Therefore, without Galileo, European critical infrastructure will rely on a system owned and operated by a foreign military power. However, the United States concluded that this idea was not in its best interest. Nevertheless, the final negotiations with the U.S. showed their conditioned approval, especially after China's involvement in funding the Galileo project, in a way that would not affect the interest of U.S. interests. Yet, China's involvement was used by the EU as a pushing card towards the final approval.

The security independence: The European security perspective has changed over the past years. Therefore, Galileo will play an important role in the future defense of the EU. Historically, Europe has depended on the United States for security since the end of World War II. Yet, the EU security was faded by America's reluctance to prosecute the war in Kosovo, as the American priority changed in the absence of the USSR. Furthermore, it was certainly noted that the post-9/11 environment refocused America's priorities on homeland defense and the war on terrorism. Hence, Europe insists that the Galileo system is designed specifically for the civilian purposes – as compared to GPS, which was designed during the Cold War for military purposes only. Consequently, the EU implies that Galileo will be the best choice for security of the European civilians, due to the fact that: meeting civilian needs is not the Pentagon's top priority any more.

The technological independence: It has been approved that Galileo is not the first European venture designed to overcome the technological dominance of the U.S. For example, the Europeans independently pursued the development of the Ariane launch booster against the U.S. Delta, the Airbus against the Boing aircraft, and the land communications Ericsson switches against the U.S. ones, all of these are good examples of the EU's ability of competition. Therefore, the U.S. dominance in satellite navigation technology once again threatens Europe in the technological dependence.

Thirdly, and in terms of the EU economic opportunity share in the worldwide market, it was anticipated that if the EU will establish a foothold in space racing, then the sales of the Galileo receivers are expected to increase from

€100 million in 2010 to about €875 million by 2020 or even more and this represents market penetration rising from 13% up to more than 52%. It will also drive the creation of jobs ranging from 100,000 jobs by 2020 to about 146,000 by the year 2025. In addition to driving up market share and creating jobs, Galileo will gain more and more profits through royalties and service charges (Beidleman, 2006).

In conclusion, with Galileo, Europe does not only secure a degree of political, security and technological independence from the United States, but also, it will provide Europe with an economic window of opportunity to seize the satellite navigation market away from the United States market dominance and to set a new global standard (Beidleman, 2006, p. 45). Nevertheless, things have currently been changed, interoperability and cooperation do exist in both systems. From the U.S. perspective, the history of negotiations is summarized as follows:

- Initially, the U.S. policy employed a “wait-and-see” approach towards Galileo, downplaying the need for another system and doubting Europe’s ability to pull it off.
- Officially, the United States saw “no compelling need for Galileo” because the GPS system would continue to meet the needs of users worldwide; there was a tendency in the U.S. planning to confuse the unfamiliar with the improbable.
- In February 1999, the EU announced the plans to pursue an independent system, and they obtained the approval and the funding to launch the Galileo program starting from 2002.
- In May 2000, the United States stopped degrading the GPS civilian accuracy by turning off the Selective Availability (SA) in an effort to make the GPS system more responsive to the civilian and the commercial users worldwide.
- In September 2000, the U.S. accelerated the GPS modernization phase by upgrading 12 out of the 20 Block IIR satellites, and included an additional civilian signal (L2C) and other two military signals (M-code), that were one of the root causes of the famous crisis of the U.S. economy at that time.
- Once the United States accepted that, the EU would build the Galileo system, whether the U.S. liked it or not, the policy was softened from blocking Galileo’s progress to ensuring its compatibility and interoperability with the GPS system, similarly to the internet network.
- Lately, the United States recommended a specific signal structure to be shared by Galileo’s OS and GPS B-III.
- In February 2004, the EU positively responded to the U.S. offer, and was potentially removing the last major obstacle.

Finally, and as per published by the EU Publication website in 2014, the U.S.– EU Agreement on GPS–Galileo cooperation was signed in 2004, and it had laid down the principles for the cooperation activities between the United States of America and the European Union in the field of satellite navigation. That agreement resolved all the technical, trade and security issues. Therefore, it eventually nullified the NAVWAR between both of them.

3. TECHNICAL BACKGROUND OF GALILEO W.R.T GPS

Assuming that there are differences and similarities between the two navigational systems, GPS and Galileo, a full technical and operational comparison is needed to be identified which would help to evaluate their strengths and weaknesses. Specifically, the GPS operational deficiencies from a European perspective and the extent to which level can Galileo intend to improve its performance in order to overcome those deficiencies. The main aspects of the comparison are the following:

Firstly, and in terms of purpose and sponsorship, the U.S. places priority on the security of the allied military capabilities when using GPS system, but the EU places priority of the Galileo system on the commercial viability for the civilians. In sponsorship wise, the GPS system was originally driven by the military’s need for the increased weapon accuracy. Yet, the U.S. Government had established the Interagency GPS Executive Board (IGEB) since 1996. The IGEB manages senior-level policy for GPS and is chaired jointly by both the Department of Defense (DoD) and the Department of Transportation (DoT) whilst the U.S. Air Force is still operating the system. On the other hand, Galileo emerged as a joint system of the European Commission (EC) and the European Space Agency

(ESA). Furthermore, the Galileo system is funded through a public-private partnership in which the EC and ESA provide funding in tandem with private companies participating in the project. In addition, the Galileo system will be operated by the so-called Galileo Operating Company (GOC) (Beidleman, 2006).

Secondly, and in terms of infrastructure, both the GPS and Galileo systems are subdivided into three parts: the space segment (also called satellite vehicles); the ground control segment (also called the command-and-control infrastructure); and the user segment (also called the end user or customer). The detailed comparison in this domain is as follows:

- The GPS space segment is comprised of 24 up to 30 satellites in a (Walker constellation) at an altitude of 10,898 nautical miles (roughly 20,200 Km), they are equally spaced in 6 orbital planes in right ascension around the earth, with an inclination of 55 degrees. The design of the GPS constellation guarantees that at least 5 satellites with good geometry are always seen in the sky-view to users worldwide in order to meet the accuracy requirements. Moreover, GPS currently uses two carrier signals, known as L1 (at 1575.42 MHz) and L2 (at 1227.6 MHz). Furthermore, GPS phases are historically as follow: Block I, Block II, Block IIA, and Block IIR (replenishment), Block IIF, IIR-M (for military uses on L5 separated), and finally the future modernized GPS Block III which is proposed to be fully operational in late 2022. On the other hand, the proposed Galileo space segment will perform the space navigation mission with only minor differences; therefore, the Galileo system will employ more satellites in fewer orbital planes with a slightly higher altitude and inclination. Literally, the Galileo system will consist of up to 30 satellites in a Walker constellation at an altitude of 23,616 Km, they are equally spaced within three orbital planes with a 56-degree inclination. Furthermore, it plans to employ the following signals: two signals on the E5A band centered at 1176.45 MHz, two signals on E5B band at 1207.14 MHz, three signals on E6 band at 1278.75 MHz, and three signals on E2-L1-E1 band at 1575.42 MHz (see Figure 2 below). Hence, the Galileo satellites are physically smaller, lighter and more covering the world than the GPS ones (European Space Agency, ESA, 2018), (ESA, 2018).

- The ground control segments of the two systems are very similar in operation, infrastructure and the way they are controlling the space segments to maintain them operational and healthy.

- Concerning the end-user segment (or the customer receivers), the U.S DoD initially developed the GPS system to support national security. The U.S. armed forces are still the primary intended customers for the GPS system for the Precise Positioning Service (PPS) with higher accuracy (less than 15 ft.), but the other users of the rest of the world are using the Standard Positioning Service (SPS) with less accuracy (10–20 m), especially after President Clinton's declaration to turn off the Selective Availability (SA) in May 2000, before the SA turning off, the accuracy was around 100 m. On the other hand, the EU marketed Galileo as a public GNSS dedicated to the civilian and the commercial users, and reduced Galileo's military utility. Furthermore, the Galileo provided services are more accurate and more precise than the current given services by the GPS system.

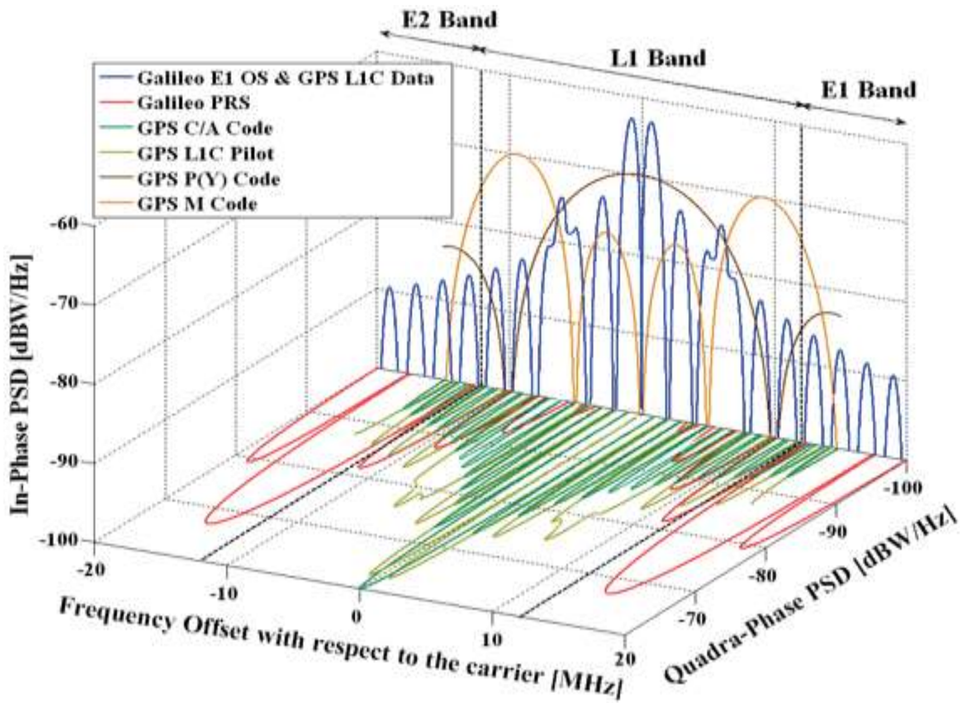

Figure 2: New Modern GNSS signal structure ((B. Eissfeller, 2007)

Thirdly, and in terms of services, there are differences between the two systems, especially the services of the Galileo system, and in specific their potential effects on the GPS system. In short, the GPS system provides the Position, Navigation, and Timing (PNT) services with two different levels of accuracy: The Standard Positioning Service (SPS) level and the Precise Positioning Service (PPS) level. The unencrypted SPS offers PNT services free of charge to all users without any alerts to users when being out of their tolerances' limits, while the PPS is dedicated for military purposes only. In contrast to GPS, Galileo plans to offer five types of services: The Open Service (OS), the Commercial Service (CS), Safety-of-Life (SoL) Service, the Public Regulated Service (PRS), and the Search and Rescue (SAR) Support Service. All of them guarantee alerts to users but not free of charge (with the exception of the Open Service [OS], which will be free). Saying that, both GPS and Galileo systems provide the basic PNT (Positioning, Navigation and Timing) services open to all users as well as the augmented services restricted to authorized users. Nevertheless, Galileo plans to offer additional features such as: the service guarantees, the global-integrity monitoring, and the additional data services supporting commercial markets; doing this for the sake of an attempt to overcome the GPS limitations from a civilian perspective.

Fourthly and lastly, in terms of limitations and vulnerabilities, both systems are identified to be vulnerable to jamming and Electronic Attacks (EA) because they are both using the electromagnetic energy in their SIS; this limitation may prevent using them in some critical applications such as the final phase of landing of an aircraft on a runway, or in other military precise missions that need weapons' high accuracy and sustainability of the used SIS. However, Galileo experimental trials showed more immune signal structure to jamming than GPS. This immunity is due to the fact of using the Binary offset Carrier (BoC) modulation scheme, and due to higher transmitted power that can mitigate high power jammers. Nevertheless, the proposed GPS Block III promises an enhanced performance as good as Galileo in this domain (Alhosban A. , 2019).

The above comparison evaluates both systems, and sheds light on how the Galileo system will be competitive to the GPS system especially in terms of the civilian services and their proposed quality. That means the initiatives of Galileo from the European perspective are highly justified and touch the top of the competitiveness as well as Galileo worthiness, with that said, Galileo is currently sharing the space with the other navigational systems in the concept of NAVWAR.

4. CHALLENGES AND THREATS

In this section, challenges and threats is addresses to the latest updates, it may change by time, and become more less, but the methodology of how to overcome them is still valid for long. This section is divided into three subsections; the first discusses the space segment challenges, the second shed the light on the ground segment challenges, and the third one examines the threats of interference on the Galileo signals. In each, the implications on NATO operations are analyzed.

4.1. Space Segment Challenges

The space segments includes the satellite vehicles, and the launchers used to put them in the dedicated orbit in the constellation, the main challenge here is not only the technical efforts and the number of satellites in view , but also the cost of each satellite vehicle, and the allocating of the necessary fund. However, The European Union Agency for the Space Program (EUSPA) selected Arianespace to launch four new Galileo satellites for Europe's satellite navigation system, according to a news release. This comes after the European Space Agency's (ESA) order to launch four satellites last October 2021, and will complete the deployment of first-generation Galileo satellites. (insidegnss-Galileo, 2022), The satellites will be launched from the Guiana Space Center (CSG), Europe's Spaceport in Kourou, French Guiana. The first launch will take place in the first half of 2022 and will carry satellites from a previous order. A second Soyuz launch in 2022 will orbit the first two satellites. Three successive launches carrying two satellites each—Ariane 62 in 2023, 2024 and 2025—will finalize the launch of the first generation of Galileo satellites Galileo I. All eight satellites will be built by OHB System AG in Bremen, Germany, and weigh less than 730 kg. They will join the 24 Galileo satellites already deployed, as well as the two to be orbited in early 2022 from the Guiana Space Center by Arianespace.

In terms of the Open Service (OS), the latest version of the Galileo Open Service Definition Document (OS SDD), updated November 2021, (Insidegnss-OS, 2022), describes upgrades enacted in the Galileo system since May 2019: improvements, current constellation status and updates in the ground infrastructure that increase its robustness. This is the last update foreseen before Galileo Open Service reaches Full Operational Capability (FOC). The updated SDD provides better Minimum Performance Levels (MPLs) for signal and position availability, updated definitions of some timing MPLs, and establishes a more stringent commitment on the time to publish Notice Advisories to Galileo Users (NAGUs).

The Galileo system, the signal propagation channel and the user equipment all contribute to the positioning accuracy experienced by the Galileo users. Table 1 presents the evolution of the horizontal and vertical expected position accuracy for the Galileo OS Positioning versus the number of operational healthy satellites. The values provided, which take into account the constraint of geometrical Dilution of Position DOP≤6, represent accuracy users would expect if they would measure their position over one complete constellation repeat cycle, from the worst user location and from the average user location. Where the performance in nominal configuration (in meters, 95% values). AUL is the Average User Location; WUL is the Worst User Location. DF is the Dual Frequency; SF is the Single Frequency.

Table 1: Evolution of the Expected Galileo OS Positioning (Insidegnss-OS, 2022)

Spatial Statics	**Service**		**Number of Satellites**	
			22	**24**
AUL	DF	H	1.8 m	1.5 m
		V	2.9 m	2.6 m
	SF	H	8.7 m	7.6 m
		V	14.0 m	12.8 m
WUL	DF	H	1.9 m	1.7 m
		V	3.3 m	3.0 m
	SF	H	9.5 m	8.2 m
		V	16.2 m	15.0 m

As it can be clearly seen, it can be concluded that the number of satellites in orbits is a challenge in the accuracy of the position measurements, consequently, it would be crucial in navigation and synchronization. If we examine the accuracy of the best configuration of DF in both WUL and AUL of the open service of PNT, the accuracy has enhanced about 20 to 30 cm in the lateral measurement when the number of satellite increases from 22 to 24 successively, the enhancement of the accuracy was from 1.8 m to 1.5 m and from 1.9 m to 1.7 m consequently, that means, if linearity would have been taken into consideration, then the complete constellation of 27 satellites (9 satellites in each orbit of the three orbits) would add three more satellites and this can double the enhancement in accuracy from 1.5 m to almost 1.2 m for AUL, and from 1.7 m to 1.4 m for WUL in 95% of the time. On the other hand, the nearly same enhancement was achieved for the most stringent requirement in the vertical position accuracy, it is about 30 cm, but from a higher error limit, from 3 m to 2.7 m, and by the same talking, with added three satellites of the full constellation of 27/3 orbits, another 30 cm might be achieved, to reach the error limit of 2.4 m, and this is the almost touching the ceiling of the requirement in GPS landing system for the vertical alert limit for example, but for other usage it would be acceptable. See Fig. 3 below.

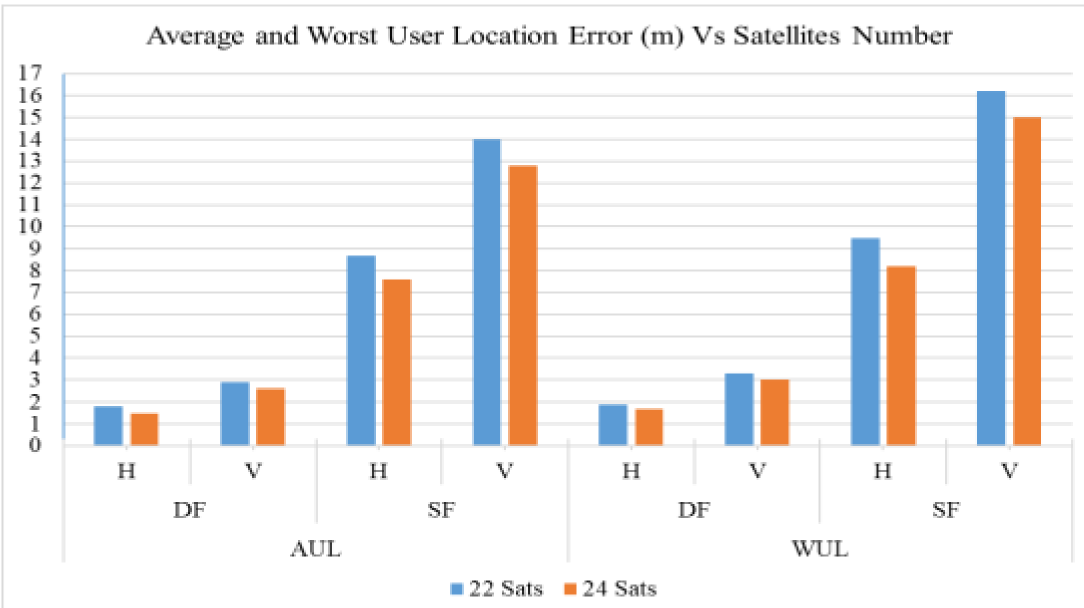

Figure 3: Average and Worst User location in meters Versus Satellites Number [edited by Author]

In general, it can be concluded that the accuracy of the open service in the new Galileo space system as expected is around ±1.5 m in the horizontal plane, and around ±2.5 m in the vertical plane, both shifted from the real position of an object in the 3D space. This is one of the challenges that might face the user/NATO adoption, if there is no RS: Regular Service for military or in case of its absence due to any reason and depending on the open service only.

Nevertheless, the navigation satellites are the most expensive, and the longest time to design and launch, moreover, a further time would be necessary to test, commission, and interoperate with the other satellites vehicles in the same constellation, moreover even with other constellations such as the modernized GPS BIII-F. see Fig. 4 below shows the actual and forecast satellite launches per year in all aspects, amongst and the least are the PNT navigational satellites, worldwide.

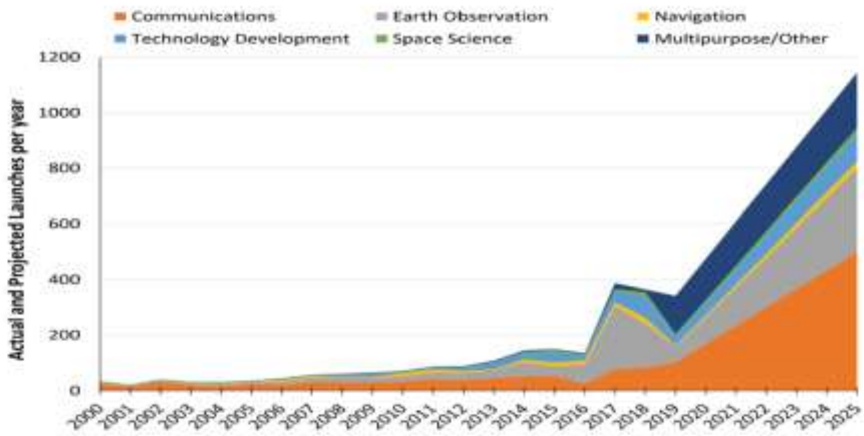

Figure 4: The actual and forecast satellite launches per year in all aspects [(BRUNNER, 2021)]

4.2. Ground Segment Challenges

On the other hand, concerning the second challenge of the ground segments, which is definitely located in the receiving side of the down link communication channel, the receivers which are used by Galileo are different from those used in GPS in circuitry design, this is due to different modulation scheme being used in both, based on that, all the current receivers have to be totally changed to match Galileo transmissions and/or GPS as well, or it could be multi-system receivers. While Dual-Frequency, Multi-Constellation (DFMC) solutions have been established in these areas, other mature safety-critical sectors lag behind, pending the finalization of standards and availability of the first certified receivers. However, the use of multiple frequencies and multiple constellations, augmentation of various types, INS hybridization, and sensor fusion all contribute to the required ‘assured’ and safe PNT positioning solutions.

The GNSS ground segments continuously evolve for better performance, reliability and security. They also need upgrades to support new signals and capabilities brought by the latest generations of satellites, such as GPS III or GPS IIIF. Consequently. As an example, the GPS ground segment is being upgraded to the ‘Next Generation Control Segment’ which is providing full operational capability to include control of both legacy and modernized satellites and signals. See Fig. 5 for Ground segment updates (Costa, 2020).

Figure 5: Ground segment updates (Costa, 2020)

In the professional domain, high-accuracy devices reign and steadily evolve towards exploiting all frequencies and constellations as they become available. Modern devices consist of compact sensor-enriched receivers, usually capable of supporting any type of augmentation service (RTK, NRTK, PPP and new PPP-RTK services) and offer flexible customization by the end user. The continued digitalization of services, the increased reliance on sensor fusion for fully-connected automated workflow management, and advanced data exploitation techniques also generate transformations in the sector. Finally, as high-accuracy geomatics solutions increasingly make inroads into other mass-market sectors, mass-market devices become increasingly able to perform low-end mapping and surveying activities. In that regard, the 'Bring your own device' (BYOD) trend is emerging, whereby surveyors and mappers use their own smartphones as an alternative to proprietary data collection devices. (Alhosban A. , Assessing Availability of GNSS-GBAS Landing Systems in GAST-D/F Performance, 2022)

Regarding timing devices that deliver time and synchronization solutions for the telecom, energy, finance or transport sectors, and research and development efforts have been made at various levels of the timing processing chain. In particular, multi-frequency and multi-constellation adoption as well as innovative Time-Receiver Autonomous Integrity Monitoring (T-RAIM) and interference monitoring algorithms aim to respond to the common demand for improved accuracy, increased resilience and improved availability. Contrary to existing radio networks where positioning has only been an add-on feature, the 5G mobile radio networks the positioning is seen as an integral part of the system design and will play a key role, enabling a huge amount of different location-based services and applications.

Technologies deployed in 5G networks include a wide bandwidth for better time resolution, new frequency bands in the mm-wave range and massive antenna arrays, which in turn enable highly accurate Direction of arrival (DoA) and Time of Arrival (ToA) estimation especially in direct line-of-sight conditions. This makes 5G networks a convenient environment for accurate positioning, targeting meter or even sub-meter accuracies. This is all the more true as the networks will get denser, e.g. in urban and deep urban environments where GNSS reception is difficult or denied. Thus, it is expected that hybrid GNSS/5G will be the core of future location engines for many applications in the Internet of Things (IoT) domains, with a significantly improved location performance in cities.

Anyway, this huge transition to the new Galileo receivers, or multimode receivers, is the significant challenge for NATO as well as other users, it would be a huge time and cost constraints for adopting the new signal processing in PNT domain, and in two paths: the multi-constellation receivers and the multi frequency receivers, illustrated below.

Concerning the multi-constellation receivers; The vast majority (76%) of current receivers are multi-constellation as per the first quarter of 2020, the latest could be found due to Covid-19 blockage (Costa, 2020), and the most popular way to provide multi-constellation support is to cover all constellations, which represents 52% of receivers, an increase of 20 percentage points (p.p.) over the last 2 years before 2020. This trend is mainly fueled by increased Galileo and Beidou support. GLONASS, QZSS and NavIC also show increased support, although to lesser extent. The legacy use of single or dual GNSS (GPS/GPS+GLONASS) is reserved for applications with stringent power limitations or low performance requirements, or where regulations have not yet been updated to multi-constellation. The multi-constellation is by far the preferred configuration owing to the benefits, it brings to receiver performance, particularly in environments with constrained view of the sky such as urban canyons. The range of benefits includes:

- Increased availability: particularly in the aforementioned constrained environments, where shadowing would prevent a single constellation from providing an adequate, or in some cases any, solution.

- Increased accuracy: better geometry, and more signals which allow the receiver to reject compromised inputs (e.g. from multipath).

- Improved robustness: several independent systems are harder to spoof than a single source.

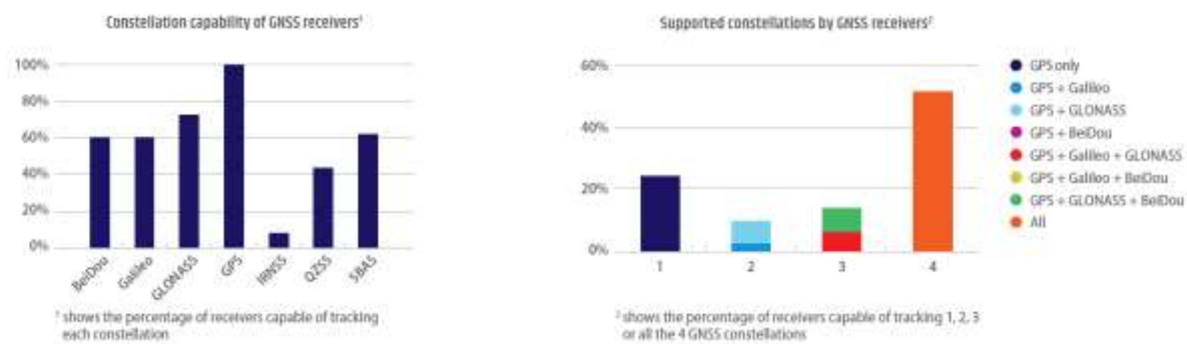

Figure 6: Analysis of GNSS receivers' capabilities / multi-constellation

Concerning the multi frequency path, as new signals become available from an increasing number of satellites, receivers beyond the traditional high-accuracy applications now feature multi-frequency support for better performance. Second generation dual-frequency receivers for the mass market became available in 2020, and are being actively developed for traditionally long lifecycle regulated domains. The primary driver beyond this trend is the increasing number of open signals in the E5 band, already outnumbering those in L2 (the legacy choice for a second frequency), and their adoption in many receiver models. This has resulted in a steady increase in production of receivers that support E5 over the last two years, and reduction in those that support L2. In the current transition period (E5a/L5 signals rapidly outnumber those in L2), several dual frequency mass market chipsets offer a configurable second frequency (either L2 or E5) that is selected by the customer when placing the order.

In the interest of simplicity, reporting frequency capability at the frequency band level, namely the L1, L2, E6 and E5 bands, as an example, for Galileo E5 only, one can use the E5a (BPSK), E5b (BPSK), and E5a+b (MBOC) signal components, or any combination thereof. Whatever the case, such a receiver will be reported as 'E5 capable'. (Alhosban A. , 2023)

The chart in Fig. 7 below represents the (2020) preferred choices of frequency bands. As previously noted, some products are reported as triple frequency (L1+L2+E5), based on claimed capability; while they are delivered to the customer as dual frequency. This results in an artificial decrease of dual frequency products, and corresponding increase in those with triple frequency capabilities.

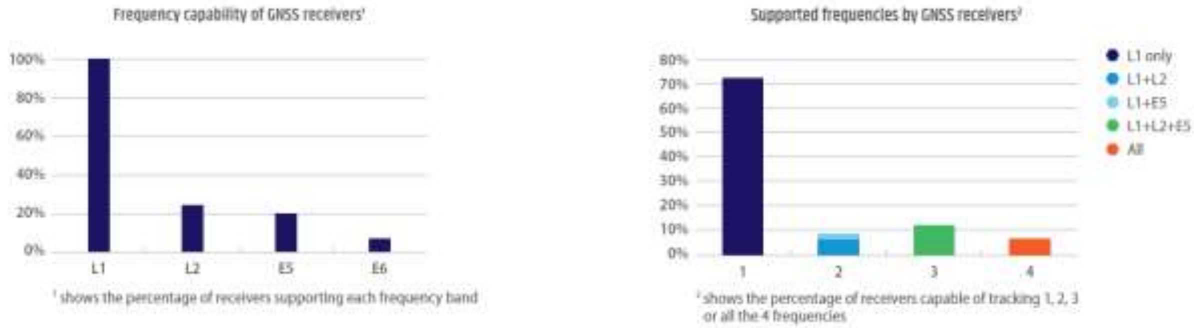

Figure 7: Analysis of GNSS receivers' capabilities / multi-frequency

In both paths, the multi-constellation and the multi-frequency receivers, the European GNSS Agency (GSA's) mission is to support European Union objectives and achieve the highest return on European GNSS investment, in terms of benefits to users and economic growth and competitiveness. Therefore, the GSA's independent analysis assesses the capabilities of almost 500 receivers, chipsets and modules currently available on the market (end of Q1 2020). For the analysis, each device is weighted equally, regardless of whether it is a chipset or receiver and no matter what its sales volume is. The results should therefore be interpreted as the split of constellation support in manufacturers' offerings, rather than what is in use by end users. The below charts in Fig. 6 below reflect manufacturer's publicly available claims regarding their product's capabilities and judgement on the domains to which they are applicable. Use in actual applications may vary due to issues such as certification, implementation in the end user product, and software/firmware configuration.

As a conclusion; the frequency capability and the constellation capability of eth supported receivers is still evolving in quantity and quality, and it might take longer time and more cost to meet the critical users as NATO, in order to adopt the new receivers in the their assets in the mission essential operations.

4.3. Threats of Interference

Ensuring both safety and security of the PNT solutions remains a key driver of technology developments and innovations. In addition, it would the third challenge of the adopting the new space-based technologies. Therefore, the protection measures against GNSS jamming and spoofing are implemented through different combinations of technologies on both receivers and antennas, through the use of multiple sources of positioning information as well as the authentication of GNSS signals (Alhosban A. , 2019). The Galileo authentication capabilities (Open Service Navigation Message Authentication and Commercial Augmentation Service – OS-NMA and CAS, respectively) are expected to provide good enhancements in this regard (Costa, 2020).

The security of PNT-based applications must be ensured at all stages, the GNSS vulnerabilities are now commonly acknowledged, and widely described e.g. in previous editions of this report. However, for users who entrust their safety or security to PNT-based systems or applications, the trust or confidence goes beyond GNSS and must encompass the end-to-end-application, which is only as safe or secure as its weakest component. This need for an overall 'trust perimeter' is schematically described in figure 8 below. The 'trust perimeter' of a typical LBS application contains many interconnected building blocks. Every block and connection is contributing to the overall security, or lack thereof.

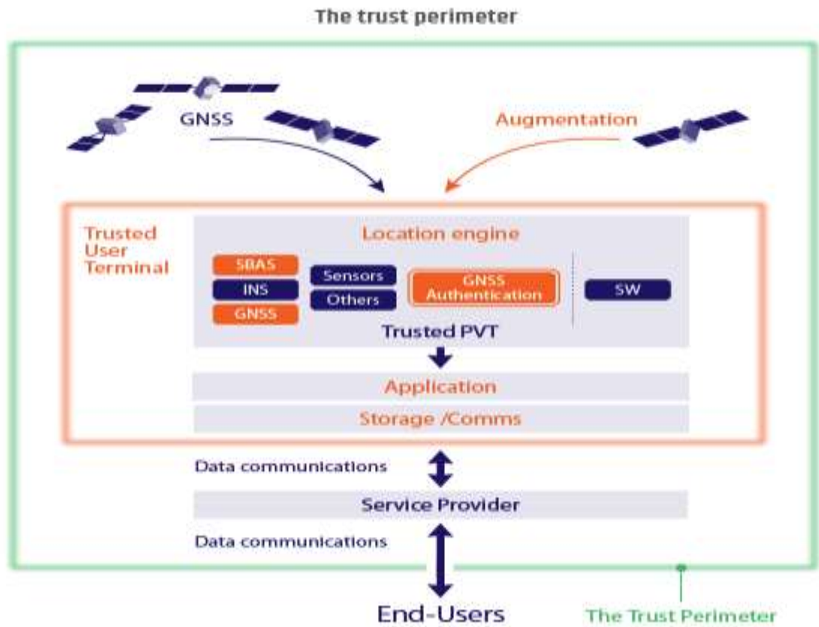

Figure 8: The trust perimeter (Costa, 2020)

As immediately apparent, GNSS is but one component in a complex system, and not necessarily the easiest to attack for maleficent actors: It might be easier or cheaper to hack the output of a receiver to report fake positions than to spoof the incoming GNSS signals. This is e.g. how maritime AIS can report positions thousands of miles away from the vessel's true position: out of reach of any spoofer, the non-secure communication link is the 'point of attack'. Thus, GNSS authentication is a necessary building block of the overall application security, but not the only one. Appraising the jamming and spoofing threats, the GNSS jamming incidents are reported in very large numbers, the vast majority of them caused by so-called 'privacy protection devices' (illegal in most countries). A wide variety of tools allow the detection, classification, and even geolocation of jammers. These include both terrestrial and space-based means, as recently demonstrated by researchers at the University of Texas at Austin1. However, no internationally coordinated effort to deploy jamming monitoring means or to prosecute offenders exist as yet. This is in spite of the extent of potential damages.

GNSS spoofing (including meaconing) incidents are less frequently reported, but they are increasing in number, and spectacular. The explanation for the lower numbers is that successful covert spoofing attacks are not detected or not reported by their victims for security reasons. Regarding the growing number of detected spoofing attacks, it must be noted that these are of a new type: the culprits apparently do not attempt to be covert, but to deny GNSS usage. Indeed, as stated by the University of Texas at Austin researchers 'spoofing is more efficient for denial of service than jamming: a 1 watt spoofer is more potent than a 1 kilowatt narrow/wideband jammer at the same stand-off distance'. The widely reported 'Black Sea' spoofing, effectively resulting in the loss of GNSS services over the area. The colored lines show ships positions jumping from truth to the location of certain airports. A rather crude 'GNSS repeater' as freely marketed for providing seamless indoors coverage could actually spoof all GNSS receivers in the vicinity of its own position, if used improperly.

CONCLUSIONS

NATO has additional options to improve resiliency by integrating the European Galileo constellation. This chapter focus mainly on the military implications of these two Global Navigation Satellite Systems (GNSS), to order to enrich the knowledge of the NATO members and policymakers about the PNT options available to the alliance, as well as addressing the various threats and challenges facing the PNT services. Challenges and threats is addresses to the latest updates, it may change by time, and become more less, but the methodology of how to overcome them is still valid for long. NATO essential missions have to comply with new requirements of Galileo in terms of Ground segments and anti- jamming protection methods. Even though the decision of adopting the new GNSS evolving space-based technology has been made, but it is still the beginning of the way to its implementation in reality.

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