NATIONAL AND KAPODISTRIAN UNIVERSITY OF ATHENS

SCHOOL OF SCIENCE
DEPARTMENT OF INFORMATICS AND TELECOMMUNICATIONS

POSTGRADUATE PROGRAM
"SPACE TECHNOLOGIES, APPLICATIONS AND SERVICES"

MASTER THESIS

Global and Regional Navigation Satellite Systems: Security and Defense Applications and Intentional Threats against them

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ATHENS

DECEMBER 2022

ΕΘΝΙΚΟ ΚΑΙ ΚΑΠΟΔΙΣΤΡΙΑΚΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΑΘΗΝΩΝ

ΣΧΟΛΗ ΘΕΤΙΚΩΝ ΕΠΙΣΤΗΜΩΝ
ΤΜΗΜΑ ΠΛΗΡΟΦΟΡΙΚΗΣ ΚΑΙ ΤΗΛΕΠΙΚΟΙΝΩΝΙΩΝ

ΔΙΙΔΡΥΜΑΤΙΚΟ ΠΡΟΓΡΑΜΜΑ ΜΕΤΑΠΤΥΧΙΑΚΩΝ ΣΠΟΥΔΩΝ
"ΔΙΑΣΤΗΜΙΚΕΣ ΤΕΧΝΟΛΟΓΙΕΣ, ΕΦΑΡΜΟΓΕΣ ΚΑΙ ΥΠΗΡΕΣΙΕΣ"

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Δεκέμβριος 2022

ABSTRACT

Satellite navigation is a space capability that provides positioning, velocity and time information to users equipped with the suitable receiver and today has a significant influence on everyday life. Currently, four global navigation satellite systems with global coverage are operational; furthermore, two regional navigation satellite systems cover only specific areas. In this master thesis satellite navigation and its basic principles of operation are described. The global and the regional navigation satellite systems as well as a technical comparison between these systems are presented. This thesis also discusses satellite navigation applications concerning security and defense issues, which are of great importance for both military and civil sectors. The intentional threats against the navigation satellite systems, that is, jamming and spoofing interference of the signal of these systems, are presented and some of the most important techniques for detection and mitigation of these threats are discussed. The conclusions of this thesis concentrate on improving the performance of the navigation satellite systems, and reducing the vulnerability of these systems towards the intentional interference against them.

SUBJECT AREA: Satellite Navigation

KEYWORDS: satellite, navigation, applications, security, interference

ΠΕΡΙΛΗΨΗ

Η δορυφορική πλοήγηση είναι μία διαστημική ικανότητα που παρέχει υπηρεσίες σχετικές με πληροφορίες για τη θέση, την ταχύτητα και τον χρόνο σε χρήστες εξοπλισμένους με κατάλληλους δέκτες και που σήμερα έχει μεγάλη επιρροή στην καθημερινή μας ζωή. Επί του παρόντος, τέσσερα παγκόσμια δορυφορικά συστήματα πλοήγησης με παγκόσμια κάλυψη βρίσκονται σε λειτουργία· επιπλέον, υπάρχουν δύο περιφερειακά δορυφορικά συστήματα πλοήγησης που καλύπτουν μόνο συγκεκριμένες περιοχές. Σε αυτή τη διπλωματική εργασία περιγράφονται η δορυφορική πλοήγηση και οι βασικές αρχές λειτουργίας της. Παρουσιάζονται τα παγκόσμια και τα περιφερειακά δορυφορικά συστήματα πλοήγησης, καθώς και μία τεχνική σύγκριση μεταξύ αυτών των συστημάτων. Αυτή η διπλωματική εργασία κάνει επίσης μία συζήτηση για τις εφαρμογές της δορυφορικής πλοήγησης που αφορούν σε θέματα ασφάλειας και άμυνας, τα οποία είναι πολύ σημαντικά και στους δύο τομείς, τον στρατιωτικό και τον πολιτικό. Παρουσιάζονται οι σκόπιμες απειλές εναντίον των δορυφορικών συστημάτων πλοήγησης, δηλαδή οι παρεμβολές θορύβου και παραπλάνησης του σήματος αυτών των συστημάτων και συζητούνται οι πιο σημαντικές τεχνικές ανίχνευσης και μείωσης αυτών των απειλών. Τα συμπεράσματα της διπλωματικής εργασίας επικεντρώνονται στη βελτίωση της απόδοσης των δορυφορικών συστημάτων πλοήγησης και στην ελάττωση της τρωτότητας αυτών των συστημάτων απέναντι στις σκόπιμες παρεμβολές εναντίον τους.

ΘΕΜΑΤΙΚΗ ΠΕΡΙΟΧΗ: Δορυφορική Πλοήγηση

ΛΕΞΕΙΣ ΚΛΕΙΔΙΑ: δορυφόρος, πλοήγηση, εφαρμογές, ασφάλεια, παρεμβολή

To all the space enthusiasts.

ACKNOWLEDGEMENTS

I want to thank my supervisor, Associate Professor Dr. Alexandros Kolovos, for all his assistance, advice and support at every stage of this master thesis. Additionally, I would like to offer my special thanks to Professor Dr. Constantinos Cartalis and to Assistant Professor Dr. Stylianos Georgantzinos, the two members of the Evaluation Committee, for their contribution to this thesis. Finally, I would like to thank my family and friends for their encouragement and support all through my studies.

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PREFACE

The objective of this master thesis is a detailed description of the global and regional navigation satellite systems, of their security and defense applications, and of the intentional threats against these systems. For the performance of this thesis, relevant to the subject area information has been searched in articles in scientific journals, books, occasional papers, special reports (e.g., issued by the European Union) and on the internet. It must be noticed that, concerning the internet, the information was mainly derived by governmental websites as well as by websites of international organizations relevant to the subject area of this thesis.

1. INTRODUCTION

After the launch of the first artificial Earth satellite Sputnik 1, on October 4th, 1957 from the former Soviet Union, the number of satellites orbiting the Earth has increasingly grown, and nowadays, their applications play a crucial role in our daily lives [1]. More and more countries worldwide have their satellites in various orbits around Earth, and they benefit from their services.

Satellite navigation is one of the main space capabilities. It provides information about the exact position anywhere on Earth (longitude, latitude and altitude coordinates) with high accuracy, punctual time information using clocks of high precision and information about the direction of travel. In 2021, the satellites which serve navigation and positioning purposes occupy almost 5% of the total number of operational satellites which are orbiting the Earth [2].

The first-ever navigation satellite system was developed by the United States Armed Forces in the decade of the 1960s [3]. Precise location and velocity are crucial for many weapon systems.Since ships, submarines, aircrafts and missiles can calculate their position and velocity with high accuracy using signals from navigational satellites [4], navigation satellite systems were developed for military use. But, although these systems were initially used exclusively for military purposes, today they have dual use, military and civil. Their contribution to security and defense is crucial, but many of their applications are very important in our everyday life as well, such as in aviation, maritime and road transport (ships, vessels, cars, trucks and trains), agriculture or even in financial transactions.

Nowadays, navigation satellite systems offer services for the public worldwide and provide highly accurate position, velocity and time information to users on Earth by using a simple, very compact and low-cost receiver. All smartphones today are equipped with satellite navigation receivers, and the users can know anytime where they are on Earth. Furthermore, these services are available 24/7, in all weather and free of charge.

Currently, four Global Navigation Satellite Systems (GNSS) with global coverage are fully operational. Furthermore, Satellite Based Augmentation Systems (SBAS) have been developed to improve the signal of GNSS. There are also two regional systems which cover only a specific region and two more under development. Issues that can come from the operation of all these systems, are arranged by the International Committee on Global Navigation Satellite Systems (ICG) of the United Nations.

All navigation satellite systems have advantages and disadvantages which depend on their technical characteristics. The countries that have developed these systems try to improve them and modernize them via continuous research to achieve a better performance and, thus, better service to the users.

The GNSS applications are numerous and affect many aspects of human lives. Therefore, security and defense applications of the navigation satellite systems are of great importance and in many cases are vital for humans. Nevertheless, the vulnerability of GNSS in front of intentional threats is a matter of further research in order to be provided with the best possible services.

In this master thesis, Chapter 2 covers the definition, the history and the basic principles of operation of the navigation satellite systems. Furthermore, the signal's characteristics, structure, and the navigation satellites' orbit are presented. The hazards from the space environment where the satellites of the system are orbiting, the sources of errors, the criteria of performance, and the applications of the navigation satellite systems are also discussed. Chapter 3 presents all the global navigation satellite systems, the satellite based augmentation systems, and the regional navigation satellite systems, which currently operate and are under development. Furthermore, issues related to the dual use, military and civil, and the interoperability of the current navigation satellite systems are discussed. The International Committee on Global Navigation Satellite Systems of the United Nations is also presented. In Chapter 4, a technical comparison between the navigation satellite systems is performed. A critical analysis of each system is also presented. Chapter 5 focuses on the navigation satellite systems' security and defense applications, which are related to the military and civil segments. Chapter 6 examines the intentional threats against the navigation satellite systems, that is the, intentional interference, which is a crucial issue for the operation of these systems, especially these days facing the Russo-Ukrainian Conflict. The conclusions of this thesis are discussed in Chapter 7.

2. BASIC PRINCIPLES OF NAVIGATION SATELLITE SYSTEMS

2.1 Satellite navigation: definition and history

- *Satellite navigation* is defined as a method to derive location, timing and velocity of a receiver on Earth by using radio signals transmitted from satellites [5] and provides Positioning, Navigation and Timing (PNT) services. PNT is a combination of three capabilities [6]:

➢ *Positioning*, that refers to the accurate determination of location and orientation on Earth;

➢ *Navigation*, that refers to the determination of the current and desired position and of the orientation and velocity to reach a desired position;

➢ *Timing*, that refers to the determination of precise time compared with a standard (for example Coordinated Universal Time – UTC) anywhere on Earth.

The *Navigation Satellite Systems* consist of satellites with specific characteristics which are located in specific orbit, and which are connected with a network of ground stations in order to provide PNT services to the users. These systems will be presented later in detail.

- V.S.Shebashevich proposed in 1957 in the former Soviet Union that satellites could be used for navigation purposes [7]. In the United States of America (USA) the idea of satellite navigation came from the observation of Sputnik satellites. Specifically, in 1958, Drs. William Guier and George Weiffenbach, scientists of the Applied Physics Laboratory (APL) of Johns Hopkins University, were studying the orbits of the Sputnik satellites [8]: they observed that the velocity of the satellites created a Doppler shift on the received signal. The two scientists discovered that they could determine the satellite's orbit by using only one signal from the satellite. It was at that time that another scientist of APL, Frank McClure, had the idea that they could use the inverse problem, that is, by using the satellite's position they could calculate a location anywhere in the globe using the received signal from the satellite.

The world's first navigation satellite system was Transit – United States Navy Navigation Satellite System (NNSS) and was designed by APL [9]. Transit's first satellite launched on April 13th, 1960 [10]. The first ever navigation satellite system was fully operational for military use by 1964 and for civil use by 1967.

In 1967, the former Soviet Union developed its first navigation satellite system named Tsyklon, which had been replaced in the 1970s by two new systems, Parus (for military use) and Tsikada (for civil use) [10].

Today, the USA and Russia have replaced their first navigation satellite systems with two new and improved ones. Furthermore, other countries have developed global and regional navigation satellite systems, and satellite based augmentation systems, as well. All the systems which are currently operational and the others which are under development will be discussed in Chapter 3.

2.2 Principles of operation of navigation satellite systems

The operation of all the navigation satellite systems presented in Paragraph 2.1 was based on the *Doppler Effect* [10]: the satellites travel in orbits (so their orbit parameters are known) and transmit signals (on a known frequency); the frequency of the received signal, though, will differ a little from the frequency of the transmitted signal because the satellites move concerning the receiver [3]. By measuring the Doppler shift of the transmitted signal throughout the satellite's passage over the receiver (**Figure 1**), the receiver's position can be determined by using the satellite's orbital and timing data, and only one satellite signal [10].

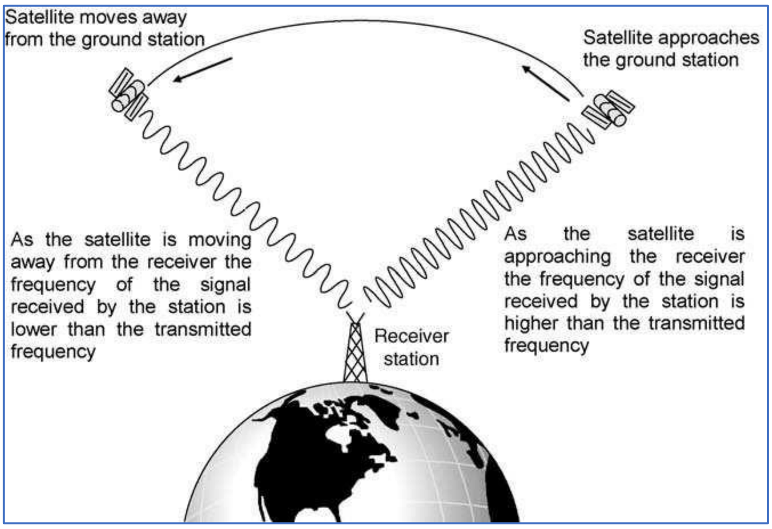

Figure 1: Navigation satellite systems using the Doppler Effect (Source: [10])

Today, the doppler-based navigation satellite systems have been replaced by systems that function by the principle of *Trilateration*, because they provide global coverage and better accuracy than the previous systems [10]. Using these systems, the receiver's position (longitude, latitude and altitude) can be determined by measuring its distance from at least three satellites (in line-of-sight contact, that is in a direct path from the satellite to the receiver) with known orbit and timing parameters. Specifically, the principle of *Trilateration* functions as follows:

The satellite transmits a signal containing its orbiting data and the precise time when the signal was transmitted [3]. It must be noticed that on board each navigation satellite there are atomic clocks of high accuracy. The receiver, by using the orbiting data, can calculate its distance from the satellite. For the calculation of the receiver's coordinates (longitude, latitude and altitude) three satellites are needed, so the receiver is at the intersection of three virtual spheres. The radius of each sphere equals to the distance between each satellite and the receiver, and in its center is the position of that particular satellite [10]. To compute the receiver's distance (D) from the satellite, the velocity of the transmitted signal, that equals to the speed of light (c), must be multiplied by the travel time required by the signal to propagate from the satellite to the receiver ($\Delta\tau$) [11]. The atomic clock on board each satellite is not precisely synchronized with the receiver's clock though, so the distance has an unknown clock error. For this reason, the measured distance is called *pseudorange* and equals to: D = c · Δτ. Using a fourth satellite can solve this problem and correct the receiver's clock errors. Thus, the receiver's position is determined at the point where all four spheres intersect (**Figure 2** [12]). Furthermore, an increased number of satellites provides more accurate positioning.

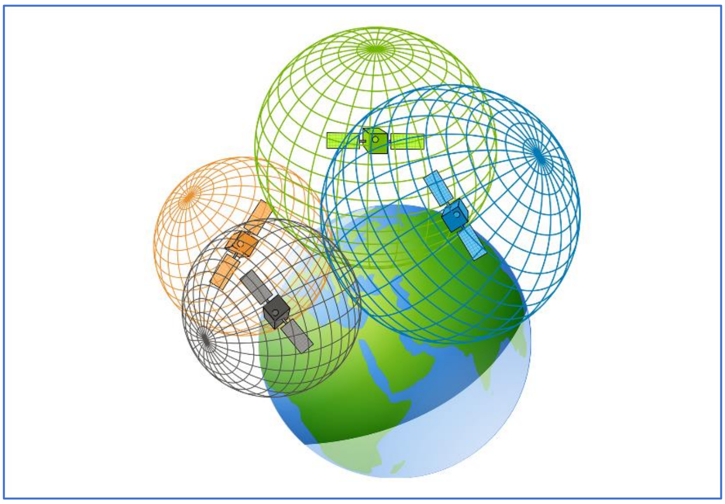

Figure 2: Position determination by using the principle of trilateration (Source: [12])

Adding the fourth satellite, we have a system of 4 equations with 4 unknowns (as the receiver's time is considered as unknown) [10]:

$$(x_1 - x_R)^2 + (y_1 - y_R)^2 + (z_1 - z_R)^2 = [c \cdot (t_1 - t_R)]^2$$

$$(x_2 - x_R)^2 + (y_2 - y_R)^2 + (z_2 - z_R)^2 = [c \cdot (t_2 - t_R)]^2$$

$$(x_3 - x_R)^2 + (y_3 - y_R)^2 + (z_3 - z_R)^2 = [c \cdot (t_3 - t_R)]^2$$

$$(x_4 - x_R)^2 + (y_4 - y_R)^2 + (z_4 - z_R)^2 = [c \cdot (t_4 - t_R)]^2$$

where:

x_n, y_n, z_n are the coordinates of the *n*th satellite

t_n is the time of the atomic clock of the *n*th satellite

x_R, y_R, z_R are the coordinates of the receiver (the first three unknowns)

t_R is the receiver's time (the fourth unknown).

From this system we can now calculate at the same time the receiver's position and time. It must be noticed that each navigation satellite system uses a reference frame so that the calculated receiver's position can have a ground reference [13].

The navigation satellite systems are used not only for the receiver's position and time calculation, but for the determination of the receiver's velocity as well. Because of the relative motion between the satellite and the receiver, the frequency of the received signal is changing, so by measuring the Doppler shift, the receiver's velocity ($\vec{v}_u$) can be calculated [11] from the equation [14]:

$$D_{Sn} = f_{Rn} - f_{Tn} = -\frac{f_{Tn}}{c} \cdot \left[(\vec{v}_n - \vec{v}_u) * \frac{\vec{r}_n - \vec{r}_u}{\|\vec{r}_n - \vec{r}_u\|} \right]$$

where:

D_{Sn}	is the Doppler shift due to the relative motion between the *n*th satellite and the user (receiver)
f_{Rn}	is the frequency of the received signal which is transmitted from the *n*th satellite
f_{Tn}	is the frequency of the transmitted signal from the *n*th satellite
c	is the velocity of the transmitted signal (which equals to the speed of light)
$\vec{v}_n$	is the velocity of the *n*th satellite
$\vec{v}_u$	is the velocity of the user (receiver)
$\vec{r}_n$	is the position of the *n*th satellite
$\vec{r}_u$	is the position of the user (receiver)
$\frac{\vec{r}_n - \vec{r}_u}{\|\vec{r}_n - \vec{r}_u\|}$	is the user-satellite line-of-sight vector.

2.2.1 Navigation satellite systems and atomic clocks

The operation of the navigation satellite systems is based on using very accurate clocks. Thus, these systems can be used as a global time source. On board the navigation satellites, there are caesium atomic clocks. This clock is a device that measures the precise length of a second (which is defined as "*the time it takes a caesium-133 atom - at rest at a temperature of 0 Kelvin - in a precisely defined state to oscillate exactly 9,192,631,770 times*") [15]. The atomic clocks are more accurate from the conventional clocks by far: they have an error of only 1 second in about 100,000,000 years, so their use in navigation satellite systems, despite their significant cost, is necessary. In the receivers there are conventional clocks because it is impracticable to have such expensive and heavy devices, so as seen in the previous paragraph, the occurred clock error can be compensated with the use of a fourth satellite in the calculation of the receiver's position.

2.3 The signal of the navigation satellites

The navigation satellites continuously transmit low-power radio signals ranging from 1 to 2 GHz frequencies (L-band) because these frequencies suffer from low rain and path losses, so they are suitable for satellite navigation [16]. The specific part of the radio spectrum in which each navigation satellite system operates (that is the Radio Navigation Satellite Service (RNSS)) is allocated from the International Telecommunication Union (ITU), the United Nation's specialized agency (founded in 1865) for allocating global radio spectrum and satellite orbits among other services [17]. It is noticed that the radio spectrum is part of the electromagnetic spectrum ranging from 3 kHz to 300 GHz (**Figure 3**) [18].

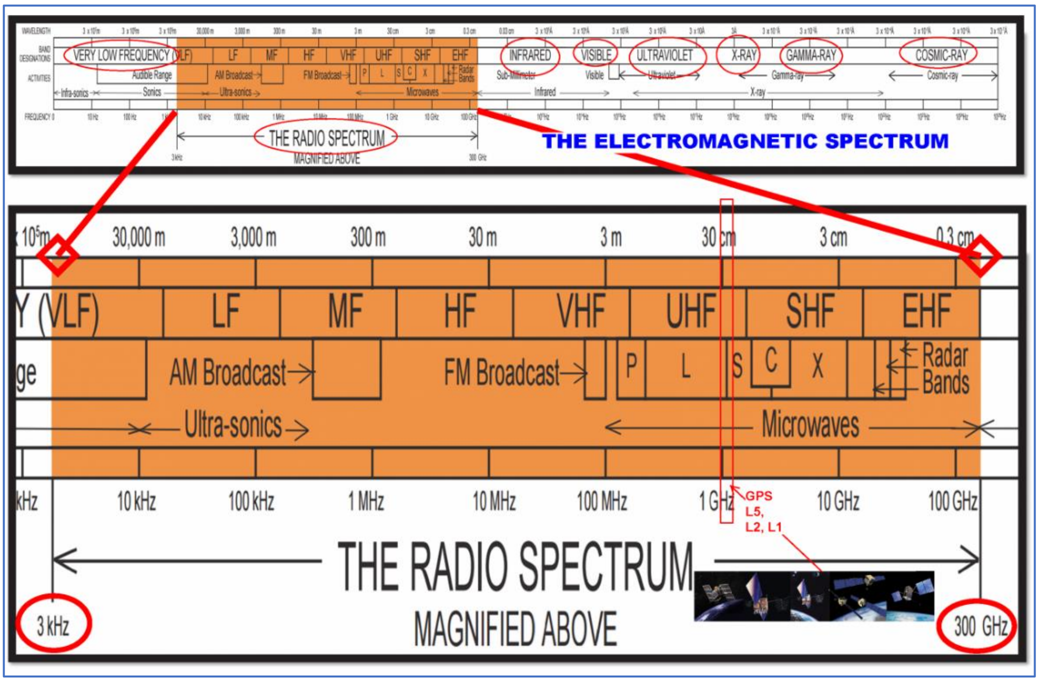

Figure 3: The Radio Spectrum (Source: [18])

2.3.1 Navigation satellites' signal structure

The navigation satellites' signal contains ranging codes and navigation data, and its main components are the following [19]:

- *Carrier*: It is the radio frequency sinusoidal signal at a given frequency. In order to send digital information in the carrier, the *modulation technique* is used [3], that is the variation of one of the three characteristics of the carrier (amplitude, phase, frequency), so that the information signal is a sequence of bits [20].
- *Ranging Code* or *Pseudo-Random Noise (PRN)*: It is a unique for each satellite code that identifies the satellite which transmits information to the receiver. PRN corresponds to a binary code (sequences of 0s a1s) [5].

➢ *Navigation Data*: It is a binary-coded message that contains information on the satellite ephemeris (that is, information about the health of the satellite and its position and velocity), almanac (that is, information about the position of each satellite anytime in the day), clock bias parameters and other information.

2.4 The orbit of the navigation satellites

The navigation satellites are placed in Medium Earth Orbit (MEO) for the following reasons [21]:

➢ MEO is a highly stable orbit that ensures accurate orbit predictions so precise knowledge of the navigation satellites' location is possible, which is a necessary condition for determining a location on Earth.

➢ In MEO, the navigation satellites' velocity is relatively slow so that they can be observed for several hours during the day.

➢ The navigation satellites being placed in MEO, can be arranged in a way that at least four of them can be seen at any time of the day from any point on Earth, which is a necessary condition for the accurate calculation of the position and the time of a receiver on Earth's surface as seen in Paragraph 2.2.

Table 1 shows the orbit parameters of the navigation satellites [22,23]:

Table 1: The Orbit Parameters of the Navigation Satellites

The Orbit Parameters of the Navigation Satellites	
Orbital Type	Semi-synchronous
Eccentricity (e)	≈ 0
Altitude	≈ 20,200 km
Inclination	≈ 55° - 64.8°
Orbital Period	≈ 12 hr
Orbital Speed	3.9 km/s

2.5 Navigation satellites and space environment

Space environment is extremely harsh, and the satellites which travel in various orbits around the Earth are not protected from the Earth's atmosphere against solar radiation and particles [23]. As seen in the previous paragraph, the navigation satellites are placed in MEO, passing through the heart of the Outer Van Allen Belt which consists of high-energy electrons. These electrons can penetrate through the satellite's shielding and cause serious damage to its instruments, so the satellite transmits incorrect data to the receiver. **Figure 4** shows one of the navigation satellites of the Global Positioning System (GPS) (which will be presented in Chapter 3) passing through the Outer Van Allen Belt [24].

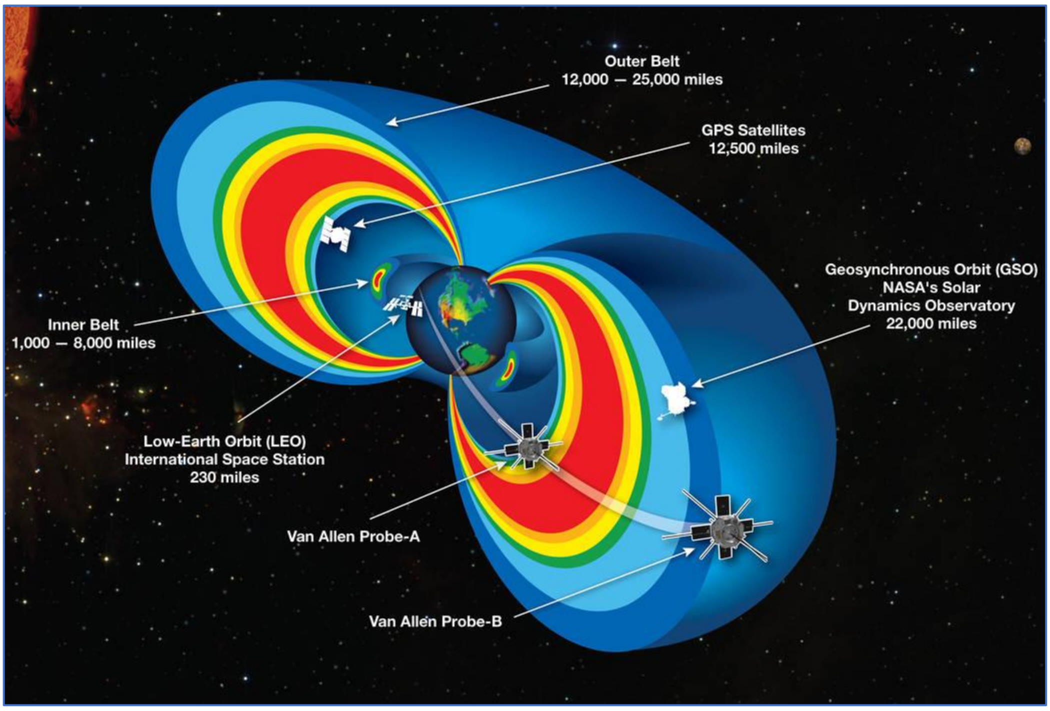

Figure 4: Radiation Belts with Satellites (Source: [24])

The changes of space environment's calm conditions that come from solar activity are described by *space weather* [23]. USA's National Oceanic and Atmospheric Administration (NOAA) has introduced the NOAA Space Weather Scales, which describe the effects of three types of space environment disturbances (Geomagnetic Storms, Solar Radiation Storms and Radio Blackouts (Solar Flares)) on satellite systems [25]. Furthermore, there is NOAA Space Weather Prediction Center which provides current space weather conditions and also alerts, watches and warnings [26] for possible problems or even outages on satellite systems such as navigation satellite systems and PNT services provided to the users.

The space weather's effects on navigation satellite systems according to NOAA Space Weather Scales are the following [27,25]:

➢ *Geomagnetic Storms*: They are major disturbances of Earth's magnetosphere due to solar wind's variations.

They can degrade navigation satellite systems' accuracy for hours or even days.

➢ *Solar Radiation Storms*: It is increased solar radiation by accelerated charged particles in the solar atmosphere to very high velocities due to a large-scale magnetic eruption.

They can cause navigation position errors.

➢ *Radio Blackouts (Solar Flares)* are increased electromagnetic radiation from the Sun in various wavelengths that last from minutes to hours.

They can cause increased errors in positioning, lasting even for several hours.

In order to compensate for the space environment and the space weather's effects on the navigation satellites, their suitable shielding is necessary.

2.6 Sources of errors in navigation satellite systems

The accuracy of positioning, navigation and timing services provided by the navigation satellite systems can be affected by several factors, which are sources of errors in these systems. The most important of these factors are the following [11]:

➢ *Satellites' clock*: The satellites' atomic clocks are synchronized, but errors occur from the minor variations between them and can cause bias on the pseudorange measurements.

➢ *Orbit parameters*: Small variations in satellites' orbit can cause errors to the system and, thus, on the pseudorange measurements.

➢ *Earth's atmosphere*: The transmitted by the navigation satellites' signal propagates through Earth's atmosphere, where mainly the ionosphere affects it and causes delays to its propagation. Global models in single-frequency receivers can mitigate the atmospheric effect.

➢ *Signal multipath*: Errors can occur when the receiver is at an environment with high buildings or mountains, so the transmitted signal can be reflected or even blocked; this can result in errors on the pseudorange measurements.

➢ *Random errors*: These errors can be occurred to the receiver due to the thermal noise of the device.

It must be noticed that the ground stations, a segment of the navigation satellite systems (which will be discussed in Chapter 3) send corrections to the navigation satellites in order to compensate the errors described above.

2.7 Criteria of navigation satellite systems' performance

There are several criteria for the evaluation of a navigate satellite system. These criteria are *accuracy*, *availability*, *continuity* and *integrity* [5,28,29]:

➢ *Accuracy*: Accurate calculations of PNT services are crucial for a navigation satellite system and significant for its performance.

➢ *Availability*: For a navigation satellite system, it is essential that its satellites are available as much as possible during the day.

➢ *Continuity*: It is paramount for the users to be reassured that the navigation satellite system they use will continue to provide its services.

➢ *Integrity*: It is the capability of a navigation satellite system to inform the users about its errors and, therefore about the limitation of system use.

In order to improve the performance of the current navigation satellite systems, Satellite Based Augmentation Systems (SBAS) are used. SBAS will be discussed in Chapter 3.

2.8 Navigation satellite systems' applications

The first navigation satellite systems which USA and the former Soviet Union had developed had only military use, as already said. Nowadays, except for the military applications of the current systems, their civil applications are numerous and concern many aspects of our daily lives. Some of the most important navigation satellite systems' applications are the following, according to the 2022 Market Report of the European Union Agency for the Space Programme (EUSPA) [30]:

- Agriculture
- Aviation and Drones
- Biodiversity, Ecosystems and Natural Capital
- Climate Services
- Consumer Solutions, Tourism and Health
- Emergency Management and Humanitarian Aid
- Energy and Raw Materials
- Fisheries and Aquaculture
- Forestry
- Infrastructure
- Insurance and Finance
- Maritime and Inland Waterways

- Rail
- Road and Automotive
- Space
- Urban Development and Cultural Heritage

Besides the above civil applications, the navigation satellite systems also provide valuable aid in the scientific domain. For example, the monitoring of the moving of Earth's crust (which is broken into rigid slabs called *tectonic plates* [31]) can be performed with navigation satellite systems' instruments placed in bedrock so that the relative movement of the tectonic plates can be measured [32].

The space-based applications of satellite navigation systems, such as the commercial use of their signals in Geostationary Orbit (GEO) [33] and Low Earth Orbit (LEO) [34] are very interesting as well. The accurate orbit determination of satellites in GEO and in LEO which navigation satellite systems can provide, reducing the cost of these missions, is currently under research.

It must be noted that the applications of the navigation satellite systems in security and defense (in the military sector) and in security and safety (in the civil sector) are of great importance and will be described in detail in Chapter 5.

3. GLOBAL NAVIGATION SATELLITE SYSTEMS, SATELLITE BASED AUGMENTATION SYSTEMS AND REGIONAL NAVIGATION SATELLITE SYSTEMS

3.1 Global Navigation Satellite Systems (GNSS)

The Global Navigation Satellite Systems (GNSS) are navigation satellite systems that provide PNT services to users globally. The architecture of all GNSS consists of three separate segments, the *Space Segment*, *the Control Segment* and the *User Segment* [5,35]:

- *Space Segment*: The Space Segment includes the constellation of the satellites of the GNSS orbiting the Earth in MEO as seen in Paragraph 2.4. The satellites are arranged into planes in a way that at least four satellites are visible at any time from the users.
- *Control Segment*: The Control Segment is a network of ground stations around the world controlling the GNSS constellation. Their task is to monitor the deviations of the orbital parameters and the satellites' clocks and make the necessary corrections when needed.
- *User Segment*: The User Segment includes all the users which receive the transmitted signals from the GNSS satellites.

Figure 5 shows the three segments of the architecture of a GNSS [35].

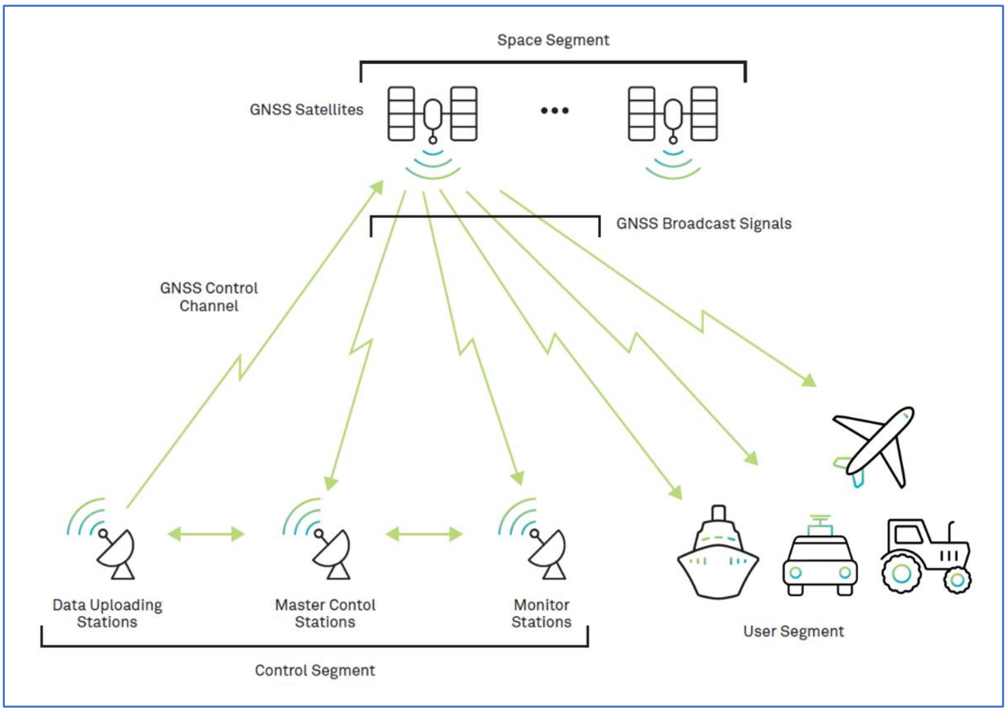

Figure 5: GNSS Architecture (Source: [35])

GNSS are reliable systems which can provide PNT services of sufficient accuracy. In some cases, though, where even higher positioning accuracy is needed, Differential GNSS (DGNSS) are used to support GNSS and there are various ways for differential positioning such as differences between observation points or satellites in view [3]. The most modern of these systems are named *Satellite-Based Augmentation Systems (SBAS)* [3], and they will be discussed further in Paragraph 3.2. Furthermore, the introduction of an Inter-Satellite Link (ISL) between the satellites of the GNSS constellation could provide higher navigation accuracy, thus, various strategies of ISL are currently studied [36].

Today, there are four operational GNSS. These systems, including the country which has developed each one of them, are the following:

- Global Positioning System (GPS) - USA
- GLObalnaya Navigatsionnaya Sputnikovaya Sistema (GLONASS) - Russia
- BeiDou Navigation Satellite System (BDS) - China
- Galileo - European Union.

The following paragraphs present descriptions of the four currently operating GNSS. The first of them, GPS, was developed by USA. Shortly after, the development of the Russian system named GLONASS has followed. Next, other countries wanted to have their own global navigation satellite system for security reasons, so the Chinese BeiDou was developed. The last of the GNSS is Galileo, the European system, which is exclusively a civil navigation satellite system with global coverage.

3.1.1 Global Positioning System (GPS)

❖ GPS History:

The world's first operational satellite navigation system was the US Navy Navigation Satellite System, also known as TRANSIT, conceived in 1962 to support the precise navigation requirements of the Navy's ballistic missile submarines.

The Global Positioning System (GPS) is the current navigation satellite system with global coverage of USA, and its full name is **NAV**igation **S**atellite **T**iming **A**nd **R**anging / **G**lobal **P**ositioning **S**ystem, NAVSTAR/GPS [37]. In the decade of 1970s, the USA's Department of Defense (DoD) decided to develop a stable navigation satellite system, whose first satellite was launched in 1978 and which became fully operational in 1993 [38]. It was Air Force Colonel Bradford Parkinson (**Figure 6**), the leader architect for the GPS, who convinced in 1973 the United States Air Force for the need of a new stable and robust navigation satellite system [39].

Figure 6: Bradford Parkinson (Source: [39])

Initially, GPS was developed only for military use but with the United States Presidential Decision Document (PDD) of March 29, 1996, it was characterized as a dual system for both military and civil use since then [28]. The operator of the military sector of GPS is the USA's Department of Defense (DoD) and for the civilian sector of GPS responsible is the USA's Department of Transportation (DoT) [28].

GPS was designed to operate with a technique called *Selective Availability*. Selective Availability (SA) was a degradation of the GPS signal when needed for national security reasons [40]. On May 1, 2000, though, the United States Government decided to terminate the Selective Availability of GPS, increasing this way the accuracy of the system for the civil users [28].

❖ Architecture of GPS:

The three segments of the architecture of GPS are the following:

➢ Space Segment [41]:

The Space Segment of GPS initially consisted of a constellation of 24 satellites. Furthermore, there were seven extra satellites (which were not part of the constellation's operational satellites), so the availability of 24 operational satellites for 95% of the time was reassured. The constellation's satellites travelat an altitude of 20,200 km arranged into 6 equally spaced orbital planes at an inclination of 55º and with an orbital period of 11 hours and 58 minutes [5]. Every one of the six planes contains four satellites. This arrangement, four satellites in each plane, reassures that at least four satellites can be viewed at any time from any point on Earth.

In June 2011, the expansion named “Expandable 24” took place, so virtually 27 satellites operate, and GPS has improved its coverage in most parts of Earth. Currently, there are 31 operational satellites in the GPS constellation. **Figure 7** presents a schematic of the Expandable 24 GPS constellation [41] and **Table 2** summarizes the orbit parameters of GPS Space Segment.

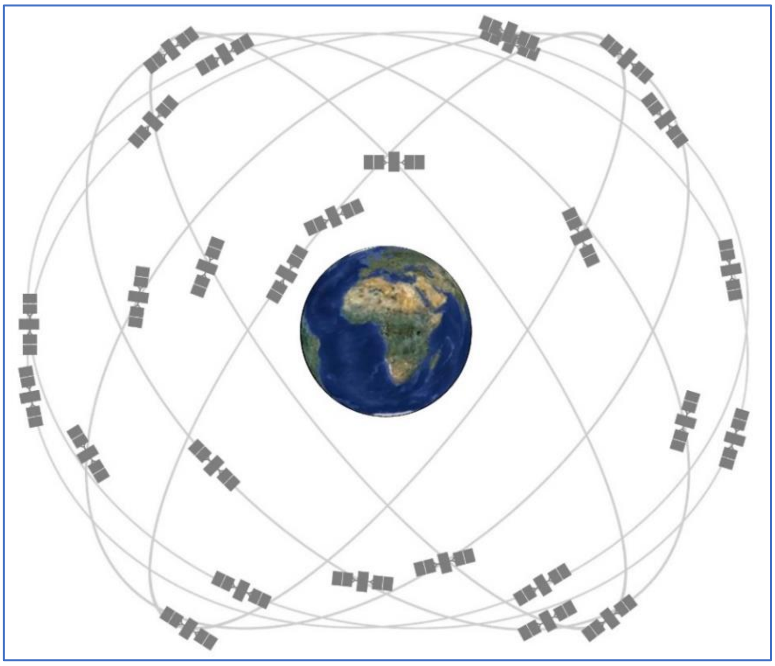

Figure 7: Schematic of the Expandable 24 GPS Constellation (Source: [41])

Table 2: The Orbit Parameters of GPS Space Segment

The Orbit Parameters of GPS Space Segment	
Altitude	20,200 km
Inclination	55°
Orbital Period	11 hr 58 min
Number of satellites	31
Number of orbital planes	6

➢ Control Segment [42]:

The Control Segment of GPS is a global network of ground stations whose task is the operational management and control of the GPS satellites. It includes a master control station, an alternate master control station, eleven command and control antennas, and sixteen monitoring sites. **Figure 8** shows the map of the GPS Control Segment network [42].

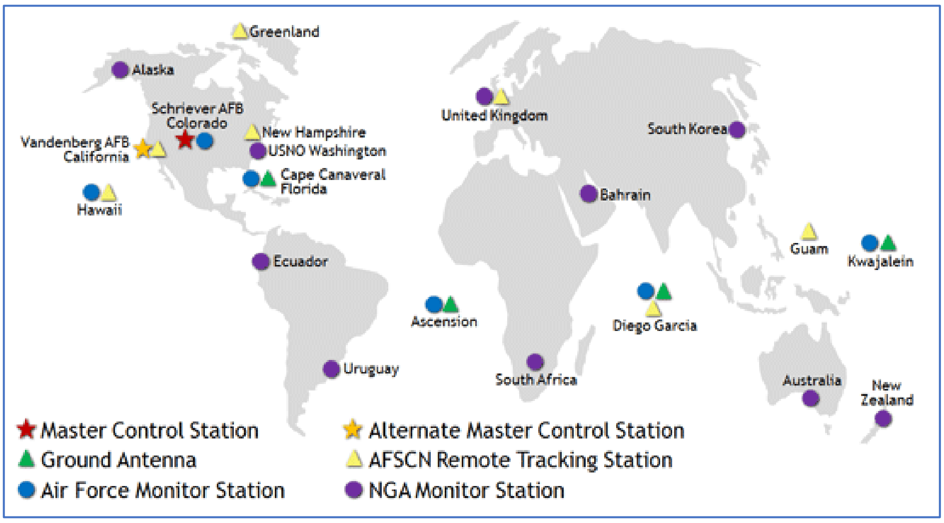

Figure 8: The GPS Control Segment Network (Source: [42])

The GPS Control Segment is operated by the Air Force Personnel of the United States Air Force's 2nd Space Operations Squadron (2SOPS) and the Air Force Reserve's 19th Space Operations Squadron (19SOPS) or "Team Blackjack".

➢ User Segment [43]:

The GPS User Segment includes all the GPS devices (receivers) that receive the signals transmitted by the GPS satellites. Both military and civil users are included in this segment.

❖ GPS signal:

The GPS signal is transmitted by each satellite of the system using the Code Division Multiple Access (CDMA) technique with a data rate of 50 bps on three frequencies [44]:

- GPS L1 Band ➲ f_{L1} = 1,575.42 MHz
- GPS L2 Band ➲ f_{L2} = 1,227.60 MHz
- GPS L5 Band ➲ f_{L5} = 1,176.45 MHz

and its PRN is divided into two codes, thus GPS provides two services [5]:

- Standard Positioning Service (SPS) or Coarse Acquisition (C/A), available for all the users.
- Precise Positioning Service (PPS) or P, available only for users authorized by the DoD.

Figure 9 shows an example of the main components of GPS L1 C/A signal [19].

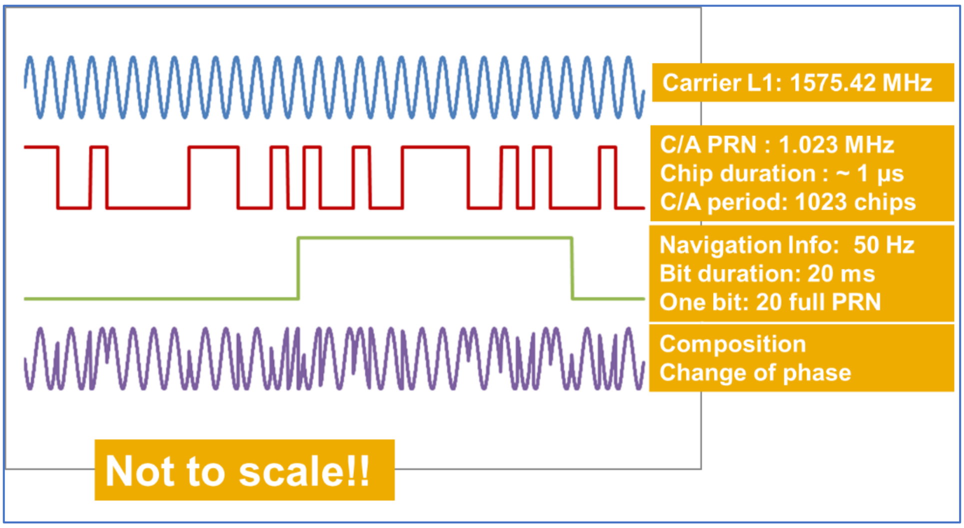

Figure 9: The main components of GPS L1 C/A signal (Source: [19])

❖ GPS Reference Frame and Reference Time:

The reference frame used by GPS is the ellipsoid model named World Geodetic System 1984 (WGS-84) which was developed by the DoD [13]. GPS time reference is the GPS Time (GPST) which is a continuous time scale that starts at 0h UTC (midnight) of January 5^{th} to 6^{th} 1980 [45].

❖ GPS PNT Performance [46]:

- GPS Positioning Accuracy: The GPS positioning accuracy commitments of the US Government apply to the transmitted GPS signal with a daily global average User Range Error (URE) of ≤0.643 m with 95% probability (on April 20, 2021).
- GPS Navigation Accuracy: The GPS velocity measurement accuracy provided by the US Government is of the GPS signal having a global average User Range Rate Error (URRE) of ≤0.006 m/s over any 3-second interval with 95% probability.
- GPS Timing Accuracy: The GPS timing accuracy relative to UTC which is provided by the US Government is of ≤30 ns, 95% of the time.

❖ GPS is an accurate and reliable navigation satellite system. Via the GPS Modernization program [47], there is a great effort to upgrade the current system and to improve its performance. However, despite its reliability, there were several incidents of malfunction. For example, in 2016, there were timing errors in GPS receivers and a 13 microseconds variation was observed. This error caused problems globally for over 12 hours [48]. Furthermore, in July 2018, it was observed a regional outage: ships reported to the North Atlantic Treaty Organization (NATO) Shipping Center that while they were transiting the Mediterranean, they faced GPS interference (which will be discussed in Chapter 6), while in December 2019, ships and aircrafts could not receive GPS signals in the Mediterranean, as NATO reported, as well [49].

❖ An important contribution of GPS was in the first Persian Gulf War in 1991 [50]: The Marines were equipped with commercial portable GPS receivers called "Sluggers (SLR's)" (from the words: Small, Lightweight GPS Receivers). Using the information provided by the GPS satellites, the Marines found their location and destination in the desert quickly and with great accuracy, compared to the other older methods using radars or other devices that the enemies could detect.

Today, GPS contributes significantly to the USA's national security [51]. Almost all of the new military equipment has GPS receivers which aid all the USA's military operations.

3.1.2 GLObalnaya Navigatsionnaya Sputnikovaya Sistema (GLONASS)

❖ GLONASS History:

GLONASS is the current navigation satellite system of the Russian Federation, and it has global coverage. The first flight tests of the system started in October of 1982 when the "Kosmos-1413" satellite launched; it has been fully operational since 1995 [7]. Initially, GLONASS was designed as a system exclusively for military use, and was operated from the Ministry of Defense, but with the Presidential Decree (1999), it became a dual use system [52]. The modernization of GLONASS was decided with the federal programs named "Global Navigation System for 2002-2011" and "GLONASS Sustainment, Development and Use for 2012-2020" which were launched in 2002 and 2012 respectively [7].

❖ Architecture of GLONASS:

GLONASS architecture consists of the following three segments:

➢ Space Segment [7]:

The Space Segment of GLONASS consists of a constellation of 24 fully operational satellites in an orbit at an altitude of 19,100 km arranged into three orbital planes at an inclination of 64.8°. There are 8 satellites in each orbital plane. The orbital period of the GLONASS satellites is 11 hours 15 minutes and 44 seconds. The constellation was developed within four time intervals and the GLONASS satellites generations are *Glonass*, *Glonass-M*, *Glonass-K* and *Glonass-K2*. **Table 3** summarizes the orbit parameters of GLONASS Space Segment and **Figure 10** presents a schematic of the GLONASS constellation [53].

Table 3: The Orbit Parameters of GLONASS Space Segment

The Orbit Parameters of GLONASS Space Segment	
Altitude	19,100 km
Inclination	64.8°
Orbital Period	11 hr 15 min 44 sec
Number of satellites	24
Number of orbital planes	3

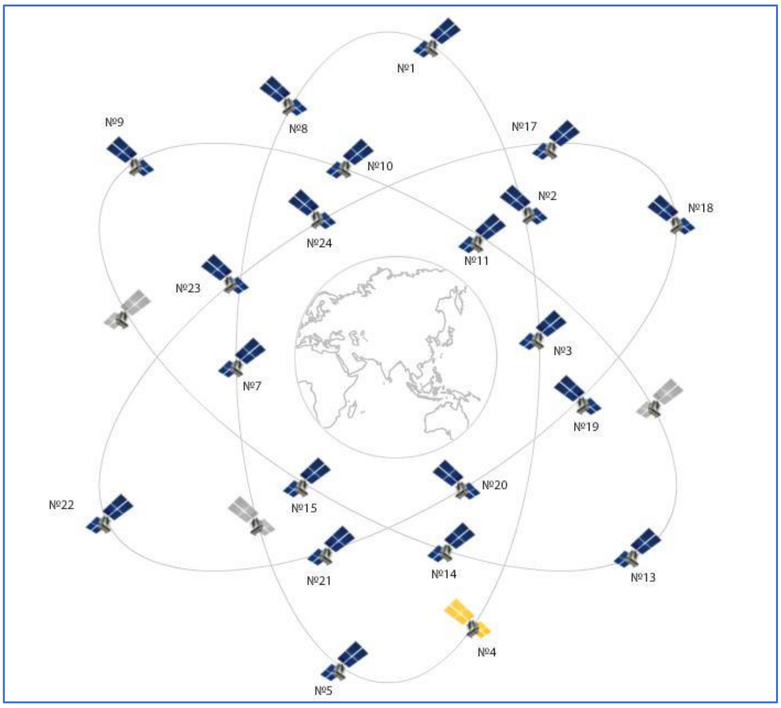

Figure 10: Schematic of the GLONASS Constellation (Source: [53])

➢ <u>Control Segment</u> [54,55]:

The GLONASS Control Segment monitors and controls the satellites of the constellation and consists of:

- A System Control Centre;
- A network of five Telemetry, Tracking and Command Centers (TT&C);
- The Central Clock;
- Three Upload Stations;
- Two Satellite Laser Ranging Stations (SLR);
- A network of four (plus six additional) Monitoring and Measuring Stations;

It must be noticed that the network of the GLONASS Control Segment is situated on the territory of the Russian Federation.

➢ <u>User Segment</u> [52]:

The GLONASS User Segment includes all the GLONASS equipped devices which receive the transmitted signals, local and regional differential subsystems, and management and control systems.

In **Figure 11** is shown the architecture of GLONASS [56].

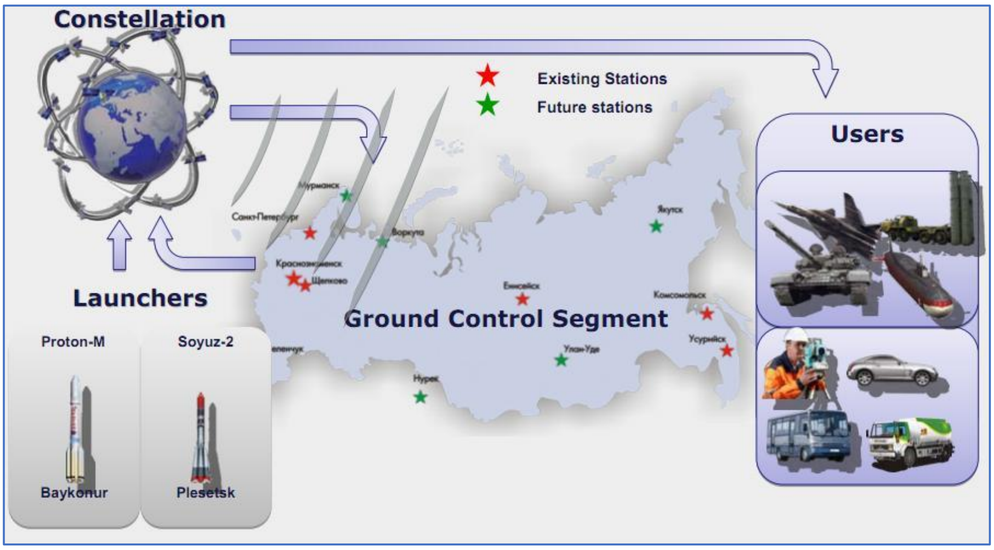

Figure 11: GLONASS Architecture (Source: [56])

❖ <u>GLONASS signal</u>:

The signal of the GLONASS satellites is transmitted using the Frequency Division Multiple Access (FDMA) technique in the L1 and L2 bands and the Code Division Multiple Access (CDMA) technique in the L3 band, with a data rate of 50 bps [54,57]:

- GLONASS L1 Band ➲ f_{L1} = 1,598.06 ~ 1,604.40 MHz
- GLONASS L2 Band ➲ f_{L2} = 1,242.94 ~ 1,248.63 MHz
- GLONASS L3 Band ➲ f_{L3} = 1,202.025 MHz

GLONASS signal uses 12 frequencies channels plus 2 channels for testing purposes; this is achieved, in the GLONASS constellation consisted of 24 satellites, by sharing the same channel every two antipodal satellites, which are in the same orbital plane but they are separated by 180 degrees [58].

It must be noticed that GLONASS can achieve interoperability (which will be discussed in Paragraph 3.1.6) with the other GNSS using the L3 band with the CDMA technique.

GLONASS transmits two types of signals and thus provides two services [7]:

- Open Access Signals (L1OF, L2OF, L1OC, L2OC, L3OC), available for all the users.
- Restricted Access Signals (L1SF, L2SF, L1SC, L2SC), for military and selected users and applications [3].

❖ GLONASS Reference Frame and Reference Time:

The reference frame used by GLONASS is the Parametri Zemli 1990 (Parameters of the Earth 1990) (PZ-90) which is a frame with a set of fundamental parameters associated [13]. GLONASS time reference is the GLONASS Time (GLONASST) which is generated by the GLONASS Central Synchroniser [45].

❖ GLONASS PNT Performance:

Initially, the PNT Performance requirements of GLONASS were [52]:

- GLONASS Positioning Accuracy: The GLONASS positioning accuracy with 95% probability should be horizontal of 28 m and vertical of 60 m.
- GLONASS Navigation Accuracy: The GLONASS velocity measurement accuracy should be of 15 cm/s.
- GLONASS Timing Accuracy: The GLONASS timing accuracy should be of 20 ns.

❖ The development of GLONASS is continued for providing better PNT services. During its operation, though, incidents of malfunctions took place. Two characteristic incidents are the following [59,49]:

- On April 1st, 2014, at 21:15 UTC, all GLONASS constellation satellites started transmitting fault Broadcast Messages (BM). This wrong BM transmitted caused an error of ± 200 km in all the three coordinates of the receivers location. For two of the GLONASS satellites the problem was solved after an hour, but for the rest of them, the problem had a duration of approximately ten hours. The operation of GLONASS was restored on April 2, 2014, at about 07:30 UTC.

- In December 2019, NATO reported that ships and aircrafts could not receive GLONASS signals in the Mediterranean, such as with GPS signals (as seen in Paragraph 3.1.1).

3.1.3 BeiDou Navigation Satellite System (BDS)

❖ BDS History:

The Chinese Beidou (Compass) Navigation Satellite System (hereafter refers to as BDS) is the third global navigation satellite system which is fully operational. The People's Republic of China has developed it according to the needs of the country's national security, and economic and social development [60]. The development of an independent global navigation satellite system was decided in the late 1990s when an incident of loss of the GPS signal occurred in 1996 during the Taiwan Strait Crisis [61]. On 31 October 2000, China launched the first navigation satellite of the system [62]. After an effort of almost twenty years, the Chinese navigation satellite system has been fully operational since 2020 and has global coverage. Initially, BDS was developed, like GPS and GLONASS, only for military use, but in 2003, it was officially opened to civil use as well [62]. The future target for BDS is establishing a PNT system with even better performance by 2035 [60].

❖ Architecture of BDS:

The three segments of BDS architecture are the following:

➢ Space Segment [63,54,3]:

The Space Segment of BDS consists of a constellation of 35 satellites: 27 in MEO (at an altitude of 21,500 km), 3 in Inclined Geosynchronous Orbit (IGSO) (at an altitude of 36,000 km), arranged into three orbital planes at an inclination of 55^o and 5 in GEO. The orbital period of the BDS satellites in MEO is 12 hours and 50 minutes.

Figure 12 presents a schematic of the BDS constellation [63], and **Table 4** summarizes the orbit parameters of the BDS Space Segment.

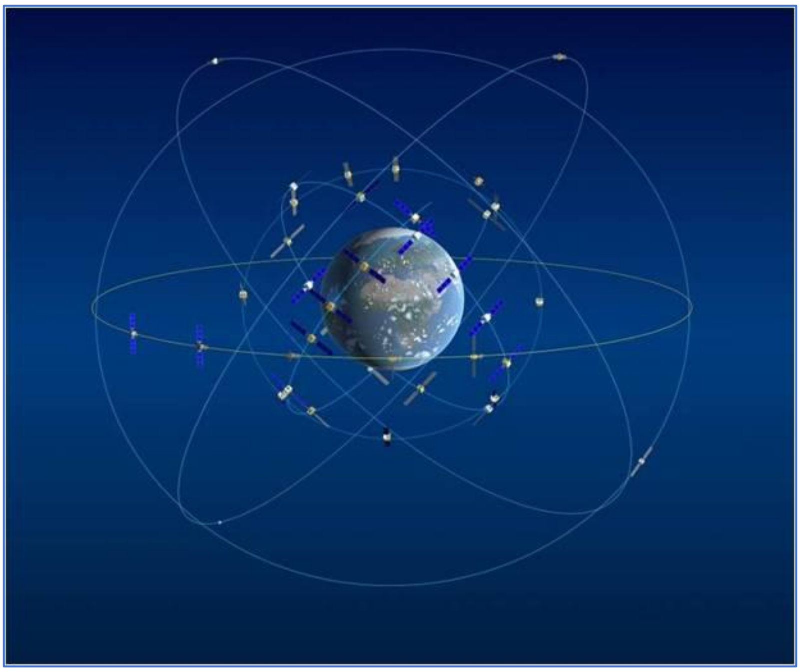

Figure 12: Schematic of the BDS Constellation (Source: [63])

Table 4: The Orbit Parameters of BDS Space Segment

The Orbit Parameters of BDS Space Segment			
Type of Orbit	MEO	IGSO	GEO
Altitude	21,500 km	35,786 km	35,786 km
Inclination	55^o	55^o	0^o
Orbital Period	12 hr 50 min	23 hr 56 min 04 sec	23 hr 56 min 04 sec
Number of satellites	27	3	5
Number of orbital planes	3	3	1

- Control Segment [64]:

The BDS Control Segment includes one Master Control Station, two Upload Stations and thirty Monitor Stations. The ground control segment of BDS is responsible for monitoring and controlling the BDS satellites, uploading orbital corrections, and the navigation message to the satellites of the BDS constellation.

- User Segment [65]:

The BDS User Segment includes all the BDS receivers which can receive the BDS signals. BDS is a two-way ranging system, that is, it uses the following technique: the Control Center emits signals to the satellites and these signals are forwarded to the receiver; then, a signal is sent back from the receiver to the Control Center via the satellites. Thus, the Control Center can calculate the position of the receiver (user) and send this information to the receiver.

- BDS signal:

The BDS signal is transmitted on the following frequency bands [54]:

- BDS B1 Band ➲ f_{B1} = 1,559.052 ~ 1,591.788 MHz
- BDS B2 Band ➲ f_{B2} = 1,166.22 ~ 1,217.37 MHz
- BDS B3 Band ➲ f_{B3} = 1,250.618 ~ 1,286.423 MHz

Today, BDS provides reliable PNT services to users all over the globe [60]. Specifically, the Chinese system provide two types of service [3]:

- *Open Service*: It is PNT services available for all the BDS users.
- *Authorized Service*: It is only for authorized users and provides higher accuracy PNT services and system integrity services, as well.

Furthermore, BDS provides two kinds of authorized service:

- A wide-area differential service (with a positioning accuracy of 1 m);
- A short-message communication service in the area of China and in the nearby areas.

❖ BDS Reference Frame and Reference Time:

The reference frame BDS uses is the BeiDou Coordinate System (BDC) which is consistent with China Terrestrial Reference Frame 2000 [13]. BDS time reference is the BeiDou Time (BDT) which is a continuous time scale that starts at 0h UTC on January 1st, 2006 [45].

❖ BDS PNT Performance:

The PNT Performance of BDS is the following [54]:

- BDS Positioning Accuracy: The positioning accuracy of BDS is of 10 m with 95% probability.
- BDS Navigation Accuracy: The velocity measurement accuracy of BDS is 0.2 m/s.
- BDS Timing Accuracy: The timing accuracy of BDS is of 20 ns.

❖ One of the great advantages of BDS is the ability that gives China to replace the GPS with its own PNT system for guiding its missiles, which is very important for the country's national security [66]. Furthermore, Pakistan is planning to end its dependence on GPS and use exclusively BDS for military and civil purposes [67].

3.1.4 Galileo

❖ Galileo History:

Galileo is a civil global navigation satellite system which is fully funded and owned by the European Union (EU), and it is operated by the European Space Agency (ESA) [68,69,70,71]: The Galileo programme started in 1999. The first two Galileo satellites were launched on October 21st, 2011 [3]. The system started its initial services on December 15th, 2016 [72]. Today, this system ensures the independence of Europe in satellite navigation. Although Galileo is a civil GNSS, the 2007 EU Space Policy provides that it could be used for defense purposes [73]. Numerous applications of Galileo facilitate the everyday life of European citizens. Furthermore, it contributes to the growth of European space industry and to the EU economy, given the fact that 7% of it depends on the availability of satellite navigation signals (concerning telecommunications, transport, etc.). The use of basic Galileo services will be free and open to everyone.

❖ Architecture of Galileo:

The three segments of the Galileo navigation satellite system are the following:

➢ Space Segment [74,75,53]:

The Space Segment of Galileo is a constellation of 30 satellites (of which six are spares) arranged in 3 equally spaced orbital planes at an inclination of 56°. The Galileo satellites orbit the Earth at an altitude of 23,222 km with an orbital period of 14 hours and 22 minutes.

Table 5 summarizes the orbit parameters of Galileo Space Segment.

Table 5: The Orbit Parameters of Galileo Space Segment

The Orbit Parameters of Galileo Space Segment	
Altitude	23,222 km
Inclination	56°
Orbital Period	14 hr 22 min
Number of satellites	30
Number of orbital planes	3

Figure 13 shows a schematic of the Galileo navigation satellite system's constellation [76].

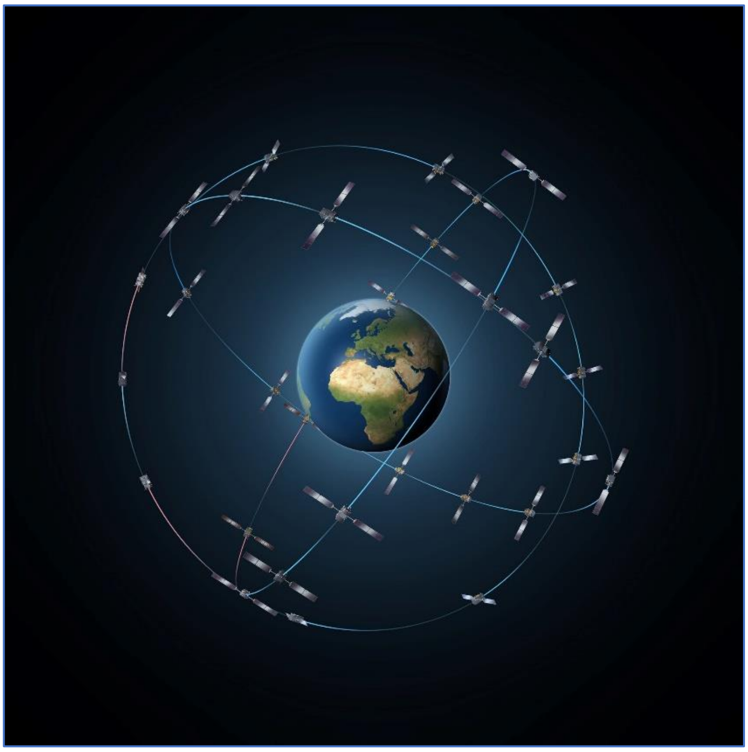

Figure 13: Schematic of the Galileo Constellation (Source: [76])

➢ Control Segment [74]:

The Control Segment of Galileo consists of two Galileo Control Centres (GCC) and includes a worldwide network of ground stations. The task of these stations is the monitoring and the control of the Galileo satellites. **Figure 14** shows the map of the Galileo Control Segment network [74].

➢ User Segment:

The Galileo User Segment includes all the receivers which can receive the Galileo satellites' transmitted signals.

Figure 14: The Galileo Control Segment Network (Source: [74])

❖ Galileo signal:

The Galileo signal is transmitted on the following frequency bands [54]:

- Galileo E1 Band ➲ f_{E1} = 1,559 ~ 1,594 MHz
- Galileo E6 Band ➲ f_{E6} = 1,260 ~ 1,300 MHz
- Galileo E5a Band ➲ f_{E5a} = 1,164 ~ 1,188 MHz
- Galileo E5b Band ➲ f_{E5b} = 1,195 ~ 1,219 MHz

Currently, Galileo provides the three following services which are free of charge and available for citizens, authorities and businesses, as well [68]:

- *Open Service (OS)*: It is PNT services available for all Galileo users.
- *Public Regulated Service (PRS)*: It is only for authorized users of EU Member States, for example, police, civil protection and other internal security services during emergencies and crisis situations.
- *Search and Rescue Service (SAR)*: Galileo aids in the location and rescue of people in danger in every environment.

Except the three current services, it is planned that Galileo will provide two more services [65]:

- *Safety of Life Service (SoL)*: It will warn the users in case of inaccurate information, including a service guarantee.
- *Commercial Service (CS)*: It will be a combination of two encrypted signals and there will be a higher data rate and accuracy.

❖ Galileo Reference Frame and Reference Time:

The reference frame used by Galileo is the Galileo Terrestrial Reference Frame (GTRF) [13]. Galileo time reference is the Galileo System Time (GST) which is a continuous time scale that the Galileo Central Segment maintains and its start epoch is defined 13 s before 0:00:00 UTC on 22 August 1999 (that is at midnight between 21 and 22 August 1999) [45].

❖ Galileo PNT Performance:

The Galileo target PNT Performance for single-frequency open service user (E1) and for dual frequency open service user (E1-E5b) is [54]:

- Galileo Positioning Accuracy: The target positioning accuracy of Galileo with 95% probability is horizontal of 15 m (E1) and 4 m (E1-E5b), and vertical of 35 m (E1) and 8 m (E1-E5b).
- Galileo Timing Accuracy: The target timing accuracy of Galileo Open Service with 95% probability is of 30 ns (E1-E5b) concerning UTC.

❖ Since Galileo started providing its PNT services, incidents of malfunction had occurred; two characteristic incidents are the following [77,78]:

- On 10 July 2019, a service incident occurred in the Galileo ground control segment, during a system upgrade. There was a great effort to solve the problem, but the result was that Galileo navigation and timing services were interrupted for six days. In order to investigate this Galileo interruption of services and to avoid similar malfunctions of the system in the future, the European Commission decided to investigate the incident via an independent Inquiry Board. The Inquiry Board delivered its findings to the Commission on 4 November 2019 and confirmed that the incident had occurred by a combination of events during the upgrade of the Galileo ground control segment. Furthermore, the

Inquire Board recommended that the service of the Galileo system must be guaranteed. This outage brought back the importance of space infrastructure security back into the spotlight.

- On 14 December 2020 between 00:00 and 06:00, incorrect data was uploaded to the Galileo satellites. This malfunction was related to a problem of a ground atomic clock in the time determination operation of the Galileo system. During the six hours malfunction, the users observed significant positioning errors.

3.1.5 Dual use of GNSS

As seen above, initially, three of the four current GNSS, that is GPS, GLONASS and BDS, were developed exclusively for military use, but nowadays, they are dual use navigation satellite systems. They provide both military and civil services. Each of the two sectors is operated by different government agencies. This mandatory cooperation has often some issues, such as the concern of the civil GNSS sector that there will be a discontinuity of services due to national security reasons [28]. Nevertheless, the two GNSS sectors work together and try to solve the issues relating to dual use, ensuring the reliability of these systems.

3.1.6 Interoperability of GNSS

One of the crucial issues relating to GNSS is their interoperability. “Interoperability” is defined as the ability of use multiple GNSS with the same equipment and without change of operating or differences in the relevant legalities [79]. If a user could use all the current GNSS together, then the provided PNT services could be improved [3]. As expected, there are issues relating to the interoperability of GNSS, except the necessary *compatibility* between them, that is the operation of these systems (separately or together) without signal interference [3]. For the interoperability of GNSS, engineering computability is achievable, but it is necessary to enact standard operating rules and legal liability, and for this, a political solution between the countries which have developed GNSS is required [79].

In order to achieve GNSS interoperability, the countries which have developed these systems participate in international organizations related to global navigation satellite systems and in agreements between them. Furthermore, there are also attempts for cooperation between these countries at the bilateral level.

3.1.7 International Committee on Global Navigation Satellite Systems (ICG)

The cooperation of GNSS is undoubtedly significant for receiving better PNT services from these systems. This is why it was decided the foundation of the International Committee on Global Navigation Satellite Systems (ICG) from the United Nations. ICG was established in 2005 and promoted the cooperation of GNSS [80]. ICG's main tasks are the following [3]:

- Compatibility and interoperability between GNSS, which are significant issues for the cooperation of the navigation satellite systems.
- Improvement of performance of GNSS services, which in many cases, such as in the GNSS security applications, is vital.
- Information propagation in order to support the greater and further use of GNSS globally.
- Geodetic and timing reference frames used by each GNSS, as well as recommendation for GNSS applications.
- Coordination between the providers of all the global and regional navigation satellite systems and other agencies responsible for the operation of these systems.

3.2 Satellite Based Augmentation Systems (SBAS)

The Satellite Based Augmentation Systems (SBAS) are geosynchronous satellite systems that improve GNSS's accuracy, availability and integrity performance. **Figure 15** shows the architecture of SBAS [81].

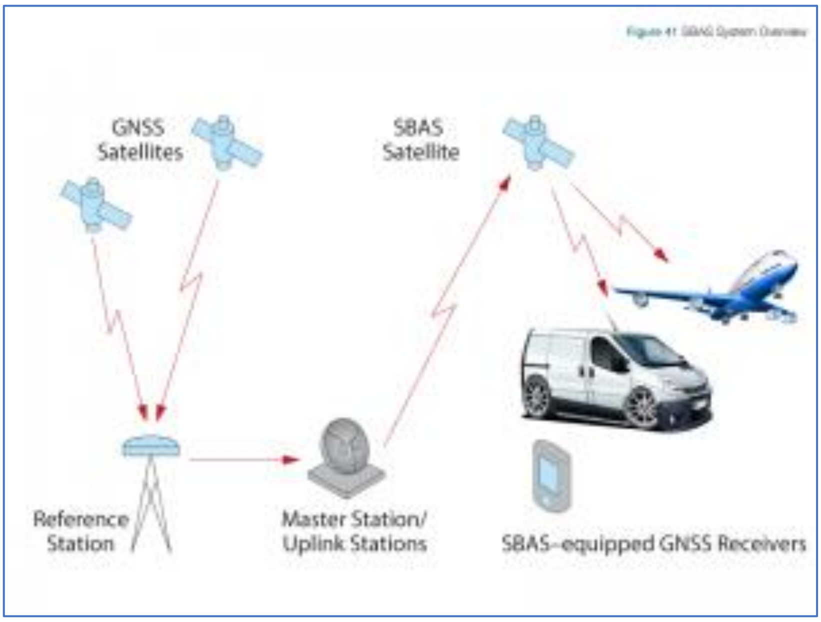

Figure 15: SBAS Architecture (Source: [81])

A Satellite Based Augmentation System consists of the following sectors:

- *Reference Stations*: These stations are geographically distributed throughout the area where SBAS services are provided. They receive the signals transmitted by the GNSS satellites and forward them to the Master Station.
- *Master Station / Uplink Station*: In this station, the errors in GNSS signals are measured and corrections are calculated. Then, these corrections are uplinked to the SBAS satellites.
- *SBAS Satellites*: They are GEO satellites which receive the GNSS signal corrections from the SBAS Master Station and then they transmit these corrections to the GNSS receivers.

Various countries have developed SBAS and more of these systems are under development, as well. In **Figure 16** the current and under development SBAS are shown [82].

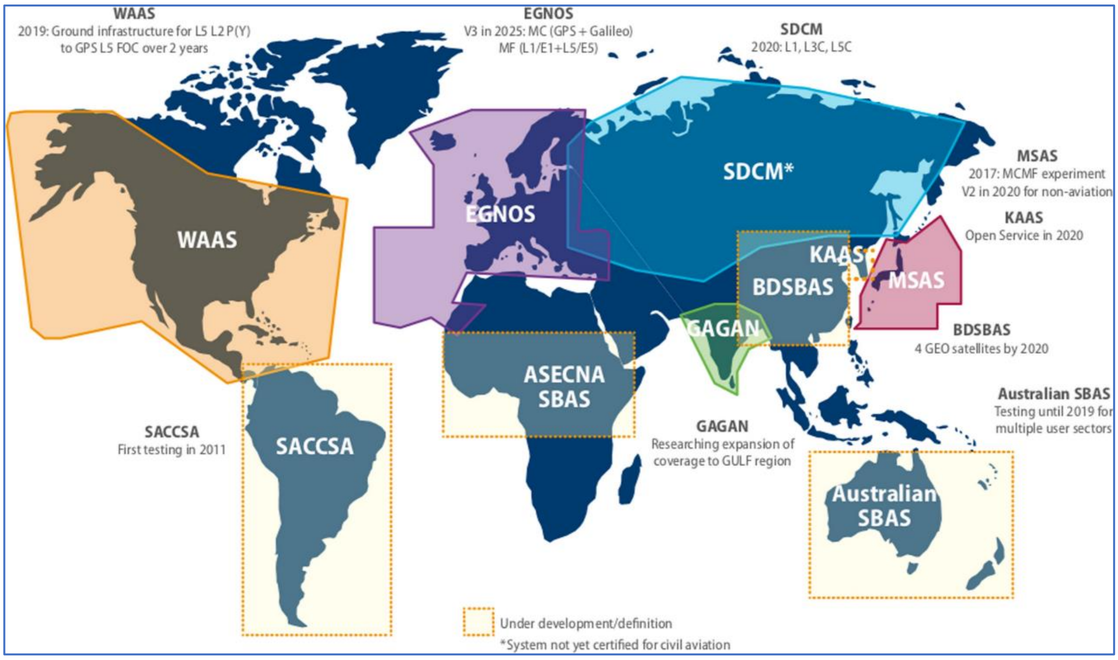

Figure 16: Current and under development SBAS (Source: [82])

Currently, there are five fully operational SBAS, which are the following (including the country which has developed each augmentation system):

- European Geostationary Navigation Overlay Service (EGNOS) - European Union
- Wide Area Augmentation System (WAAS) - USA
- System for Differential Corrections and Monitoring (SDCM) - Russia
- GPS-Aided GEO Augmented Navigation System (GAGAN) - India
- Multifunctional Transport Satellites Satellite Based Augmentation Navigation System (MSAS) - Japan

As shown in **Figure 16**, four SBAS are also under development planning to cover areas where there is not currently covered by the operational SBAS, such as South America, Central Africa, China and Australia.

3.2.1 European Geostationary Navigation Overlay Service (EGNOS)

European Geostationary Navigation Overlay Service (EGNOS) is the European SBAS which is officially operated since 1 October 2009. This system improves the accuracy of GPS (and soon of Galileo) signals in Europe [83]. Furthermore, EGNOS provides integrity information to the users.

EGNOS consists of three GEO satellites, an interconnected ground network of forty positioning stations (geographically distributed as shown in **Figure 17** [84]) and two mission control centers. Its performance is good in almost all the countries of the EU. Additionally, EGNOS can technically expand its coverage to North Africa and the Middle East [83].

Figure 17: Ground Positioning Stations of EGNOS (Source: [84])

EGNOS provides three services which are the following:

- *EGNOS Open Service (EGNOS OS)* [85]: It is available since October 1st, 2009 and provides improved accuracy to users of general-purpose applications.
- *EGNOS Safety-of-Life Service (EGNOS SoL)* [86]: This service helps the aircrafts to approach the airports with vertical guidance and improves the safety of air navigation.
- *EGNOS Data Access Service (EDAS)* [87]: It provides EGNOS data to users who don't always have access to EGNOS satellites, such as users to urban environment.

Figure 18 [88] shows the architecture of EGNOS.

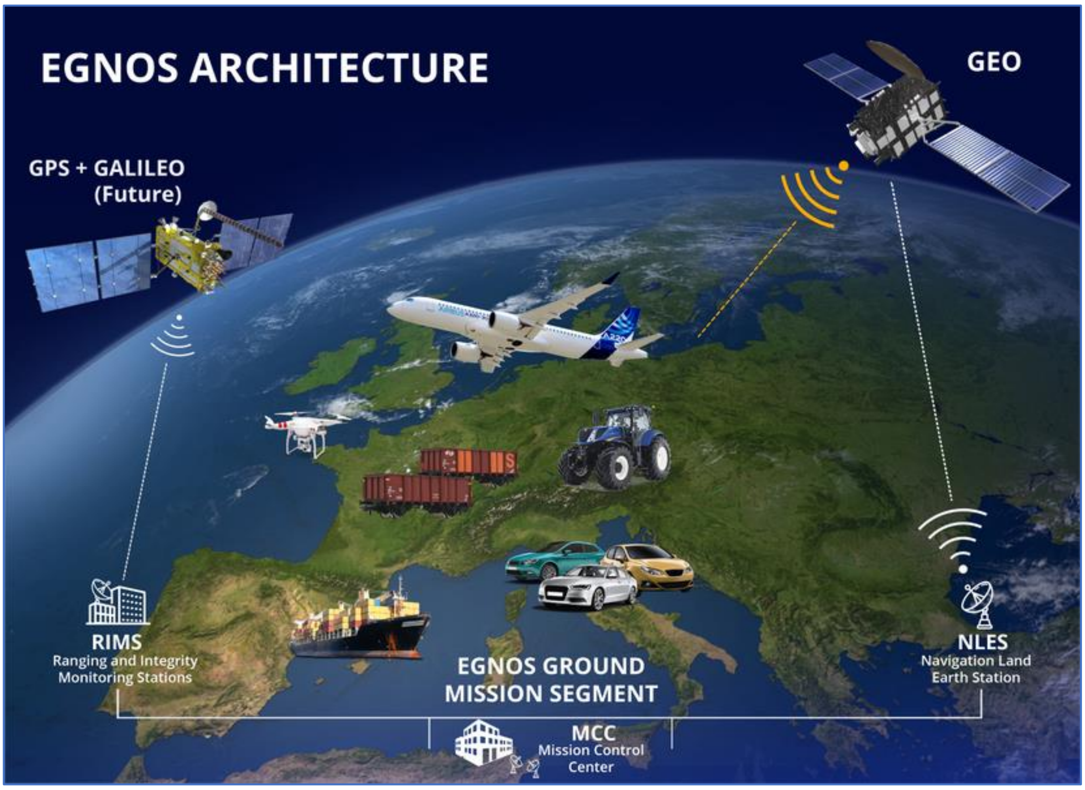

Figure 18: EGNOS Architecture (Source: [88])

3.2.2 Wide Area Augmentation System (WAAS)

Wide Area Augmentation System (WAAS) was developed by the USA's DoT and Federal Aviation Administration (FAA), as the aid of aviation was one of the main reasons for the WAAS project [89]. The development of WAAS started in 1994 and its initial operational capability phase was in January 2003.

WAAS supports aircraft navigation covering the area of North America, but it is also used widely by users from various PNT communities [90]. The WAAS users receive correction data from the system's satellites using their GPS receiver and antenna equipment, as WAAS satellites transmit their signal on the same frequency as GPS [81].

It must be noticed that WAAS is interoperable with other satellite based augmentation systems such as EGNOS and the SBAS of India and Japan (which will be presented in the following Paragraphs) [90].

3.2.3 System for Differential Corrections and Monitoring (SDCM)

The System for Differential Corrections and Monitoring (SDCM) is the SBAS developed by the Russian Federation. The system's first satellite was launched on 11 December 2011 [3]. This system improves the accuracy and the integrity of the GLONASS and GPS signals in the territory of the Russian Federation [81]. SDCM is compatible with the WAAS and other satellite based augmentation systems [3].

3.2.4 GPS-Aided GEO Augmented Navigation System (GAGAN)

The GPS-Aided GEO Augmented Navigation System (GAGAN) is the Indian SBAS which improves the GPS signal [3] and supports air navigation over India. GAGAN consists of three GEO satellites, fifteen ground stations located throughout the territory of India, three uplink stations and two control centers [81]. This system is compatible with other satellite-based augmentation systems [81].

3.2.5 Multifunctional Transport Satellites Satellite Based Augmentation Navigation System (MSAS)

The Multifunctional Transport Satellites Satellite Based Augmentation Navigation System (MSAS) is a SBAS system developed by Japan. This augmentation system uses two Multifunctional Transport Satellites (MTSAT), successfully launched in 2005 and the second in 2006 [3]. MSAS improves the GPS signal in the area of Japan [81].

3.3 Regional navigation satellite systems

The need for independence in satellite navigation due to national security reasons motivated the development of regional navigation satellite systems. Currently, two regional navigation satellite systems, which cover a specific area, are fully operational and two more are planned to operate in the future. These systems, including the country which has developed each one of them, are the following:

- Indian Regional Navigation Satellite System / Navigation with Indian Constellation (IRNSS/NavIC) - India
- Quasi-Zenith Satellite System (QZSS) - Japan
- Bölgesel Konumlama ve Zamanlama Sistemi (BKZS) - Turkey
- Korean Positioning System (KPS) - South Korea

3.3.1 Indian Regional Navigation Satellite System / Navigation with Indian Constellation (IRNSS/NavIC)

❖ Initially, India's regional navigation satellite system was named Indian Regional Navigation Satellite System, but it has been renamed Navigation with Indian Constellation (IRNSS/NavIC). This system is fully operational and provides PNT services over India and about 1,500 km around India’s boundaries as well [82].

❖ The architecture of IRNSS/NavIC consists of the Space, the Control and the User Segment (which includes all the IRNSS/NavIC receivers) [91,92]:

➢ <u>Space Segment</u> :

The Space Segment of IRNSS/NavIC consists of a constellation of seven satellites: three of the satellites are placed in GEO; four of the satellites are placed in inclined geosynchronous orbit (IGSO) in an inclination of 29º arranged into two orbital planes (in each plane there are two satellites).

➢ <u>Control Segment</u> :

The Control Segment of IRNSS/NavIC consists of a network which includes the control centre, precise time facility, and other monitoring stations responsible for the monitoring and control of the satellites of the constellation, for the ionospheric and clock corrections, and for running the navigation software.

Figure 19 shows the architecture of IRNSS/NavIC [92]:

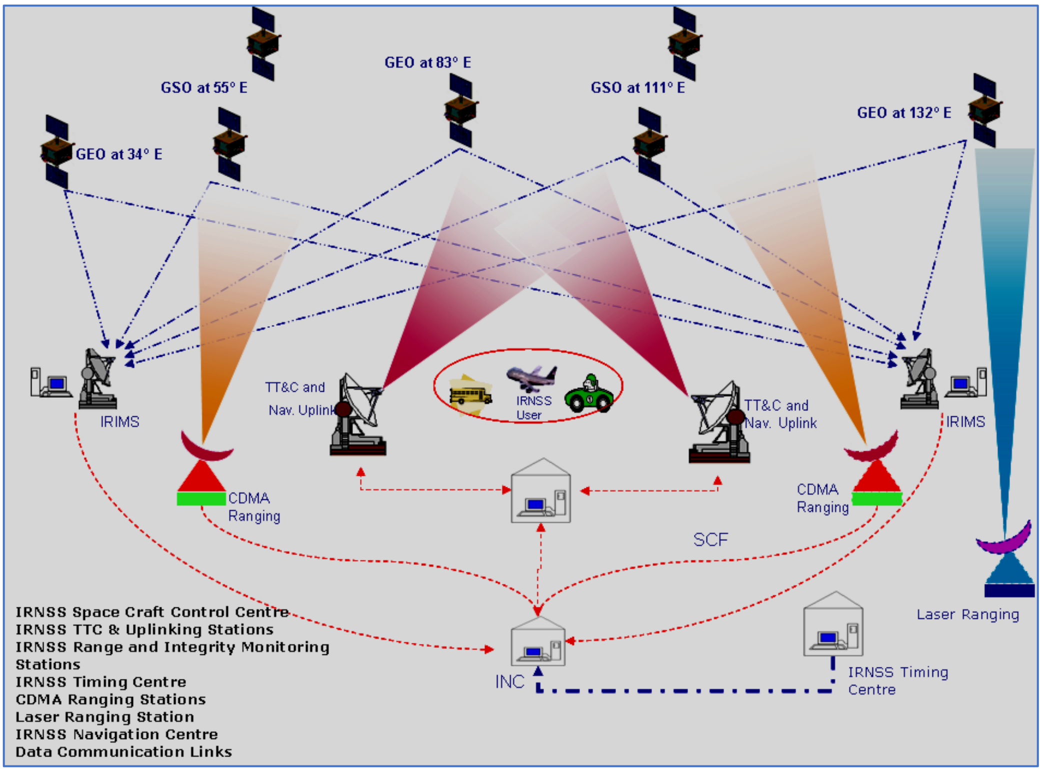

Figure 19: IRNSS/NavIC Architecture (Source: [92])

❖ IRNSS/NavIC provides two services [91,3]:

- Standard Positioning Service (SPS), available for civil users.
- Restricted Service (RS) is encrypted, and it is available only for authorized users.

❖ IRNSS/NavIC is designed to provide [91]:

- Position Accuracy better than 20 m.
- Timing Accuracy better than 50 ns.

3.3.2 Quasi-Zenith Satellite System (QZSS)

❖ Quasi-Zenith Satellite System (QZSS) is the Japanese regional navigation satellite system which provides PNT services for Japan and Oceania (East Asia) [3]. QZSS, which sometimes it is called the “Japanese GPS”, is fully operational since November 2018 [93].

❖ The architecture of QZSS includes the Space Segment, the Control Segment and the User Segment (which consists of all the QZSS users) [93,54]:

➢ Space Segment :

The Space Segment of QZSS consists of a constellation of four satellites, in a way that three satellites are visible at all times from locations in the Asia-Oceania region with a focus on Japan [93,94]. One of the satellites is in a GEO above the equator, and the other three are in quasi-zenith orbits (QZO) (each satellite in its own orbital plane in an inclination from 39º to 47º) [94,54]. QZO is a figure-eight-shaped orbit with a north-south asymmetry (**Figure 20** [94]), that is the satellites in this orbit are for 13 hours in the northern hemisphere and for 11 hours in the southern hemisphere; in this way, the satellites remain near Japan for a long period. And this is precisely the advantage of QSZZ for Japan: people in urban areas with very high buildings or in regions with mountains can have stable PNT services, that it cannot be possible with GPS signals [95].

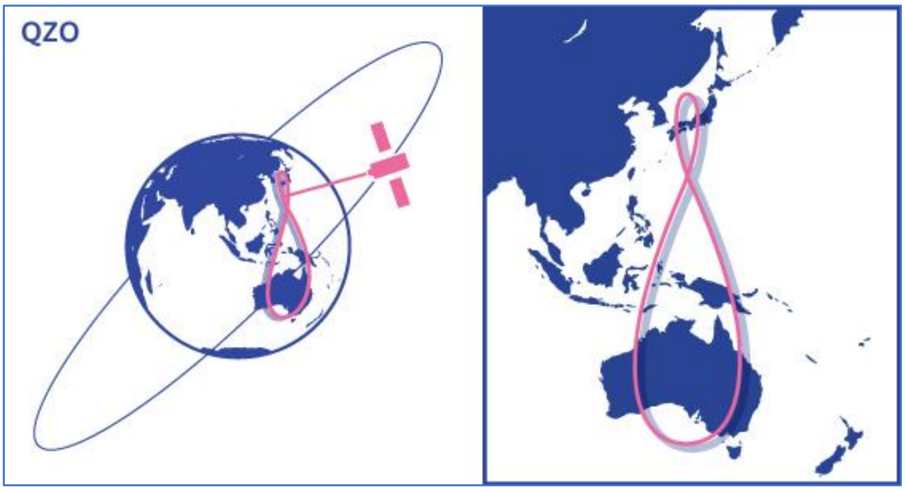

Figure 20: Satellite in Quasi-Zenith Orbit (QZO) (Source: [94])

➢ Control Segment [54]:

The Control Segment of QZSS includes a master control station located in Japan and monitor stations which are widely located around the globe. This network is responsible for the monitoring and the control of the satellites of QZSS’s Space Segment.

3.3.3 Bölgesel Konumlama ve Zamanlama Sistemi (BKZS)

Turkey, according to its National Space Program, is planning to develop a regional positioning and timing system, the Bölgesel Konumlama ve Zamanlama Sistemi (BKZS) (Regional Positioning and Timing System) [96]. With this navigation satellite system, Turkey aims to achieve independence in PNT services and increase, at the same time, position and timing accuracy for the area of Turkey and of the other countries of the region as well [97].

The inspiration of this program comes from QZSS, Japan's current regional navigation satellite system (Paragraph 3.3.2). BKZS will consist of a constellation of six to eight navigational satellites in MEO (at an altitude of about 20,000 km). Furthermore, Turkey is planning to manufacture the atomic clocks, which will be onboard the satellites of the BKZS constellation and the compatible receivers to its own industry, as well [96].

It is worth noting that the Turkish regional navigation satellite system will give a great advantage to the Turkish Armed Forces, with its installation of the cruise – JDAM (Joint Direct Attack Munition) missiles [96].

3.3.4 Regional South Korean Positioning System (KPS)

South Korean government decided in February 2018, and in its 3rd Master Plan for Space Development and Promotion, to develop its own regional navigation satellite system, named Korean Positioning System (KPS), by 2035 [98,82]. The motivation for this decision is that in the case of GPS loss of service during an emergency, KPS will provide PNT services to the Korean Peninsula.

KPS will be similar to the other two current regional navigation satellite systems (IRNSS/NavIC of India and QZSS of Japan), consisting of three satellites in GEO and four in elliptical IGSOs will cover South Korea and about 1,000 km of its surrounding area. **Figure 21** shows a schematic of the constellation's ground track (in the left) and the target area (in the right) of the planned Regional South Korean Positioning System [82].

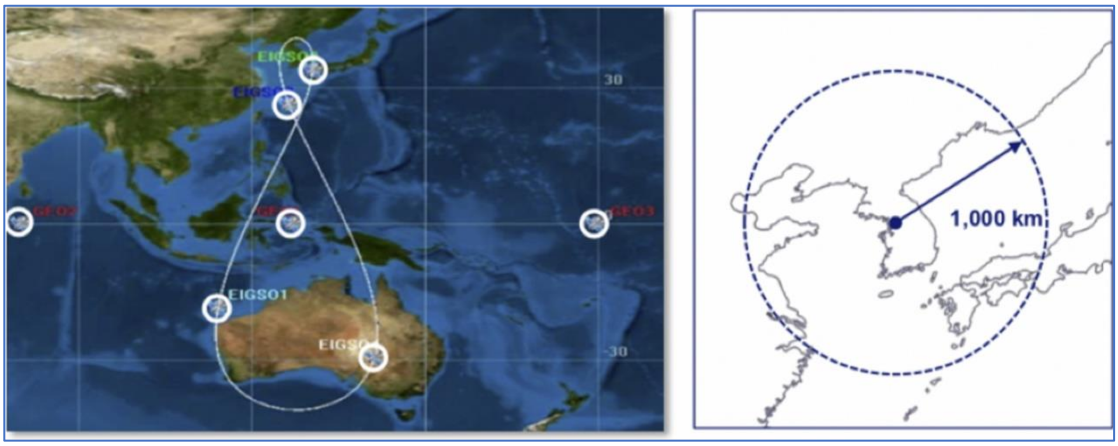

Figure 21: Constellation's Ground Track (left) and Target Area (right) of the Regional South Korean Positioning System (KPS) (Source: [82])

4. TECHNICAL COMPARISON BETWEEN THE NAVIGATION SATELLITE SYSTEMS

In this Chapter, a technical comparison of the GNSS as well as of the regional navigation satellite systems will be performed and a critical analysis of each system will be presented. The parameters of each system shown in Chapter 3 will be used for these presentations.

4.1 Technical comparison between the Global Navigation Satellite Systems

4.1.1 Parameters of GNSS Space Segment

In **Table 6** are summarized the parameters of the Space Segment (type of orbit, altitude, inclination, orbital period, number of satellites, and number of orbital planes) of each GNSS:

Table 6: The Orbit Parameters of the Space Segment of the four GNSS

Parameter	GPS	GLONASS	BDS	Galileo
Type of Orbit	MEO	MEO	MEO	MEO
Altitude	20,200 km	19,100 km	21,500 km	23,222 km
Inclination	55°	64.8°	55°	56°
Orbital Period	11 hr 58 min	11 hr 15 min 44 sec	12 hr 50 min	14 hr 22 min
Number of satellites	31	24	27	30
Number of orbital planes	6	3	3	3

It must be noticed that **Table 6** summarizes the parameters of the GNSS Space Segment concerning *only* the satellites which are in MEO.

With the aid of **Table 6**, the comparison between the parameters of the Space Segment of each GNSS, is the following:

✓ The satellites of the three systems, GPS, GLONASS and Galileo, are only in MEO. On the other hand, as mentioned in Paragraph 3.1.3, the BDS constellation consists of 35 satellites, where 27 are in MEO (as seen in **Table 6**), 3 are in IGSO and 5 are in GEO. This characteristic hybrid constellation of BDS, consisting of satellites in three different orbits, offers BDS better anti-shielding capabilities, thus better performance in low-latitude areas [60].

✓ The altitude, the inclination and the orbital period of each GNSS constellation is different. The reason for this, is that, even though all the GNSS have global coverage, first of all, they were developed to serve the country which had designed them. Thus, each GNSS has the altitude, inclination and orbital period, which are the best possible for the corresponding country. For instance, Galileo has a greater inclination (56°) than GPS (55°) in order to achieve better coverage at high European latitudes [3].

✓ The number of satellites and the orbital planes of each GNSS constellation is different; this is related to the design of each constellation in order to have the best possible global coverage.

4.1.2 GNSS Signal Frequency Bands

Table 7 summarizes the signal's band and its frequency which are used by each GNSS:

Table 7: GNSS Signal Frequency Bands

GNSS	GNSS Signal's Band	GNSS Signal Band's Frequency (MHz)
GPS	L1	1,575.42
	L2	1,227.60
	L5	1,176.45
GLONASS	L1	1,598.06 ~ 1,604.40
	L2	1,242.94 ~ 1,248.63
	L3	1,202.025
BDS	B1	1,559.052 ~ 1,591.788
	B2	1,166.22 ~ 1,217.37
	B3	1,250.618 ~ 1,286.423
Galileo	E1	1,559 ~ 1,594
	E6	1,260 ~ 1,300
	E5a	1,164 ~ 1,188
	E5b	1,195 ~ 1,219

With the aid of **Table 7**, the comparison between the Frequency Bands of the signal of the four GNSS, is the following:

✓ As seen in Paragraph 2.3, the specific part of the radio spectrum in which each navigation satellite system operates is allocated from the ITU, so there is no interference between the GNSS. In cases where the frequency bands of a GNSS overlap with the signal of another (for instance, BDS and Galileo), under the ITU policies, the first country which started the operation of its GNSS in a specific frequency will have the priority to that frequency [3].

✓ Each GNSS uses one or more access techniques for its signal, that is either the Code Division Multiple Access (CDMA) technique (that is multiple code technique) or the Frequency Division Multiple Access (FDMA) technique (that is multiple frequency technique) or both of them. For instance, GPS uses the CDMA technique only, but GLONASS uses both FDMA and CDMA.

4.1.3 GNSS's Reference Frame and Reference Time

In **Table 8** are summarized the Reference Frame and Reference Time used by each GNSS:

Table 8: GNSS Reference Frame and Reference Time

Parameter	GPS	GLONASS	BDS	Galileo
Reference Frame	World Geodetic System 1984 (WGS-84)	Parametri Zemli 1990 (Parameters of the Earth 1990) (PZ-90)	BeiDou Coordinate System (BDC)	Galileo Terrestrial Reference Frame (GTRF)
Reference Time	GPS Time (GPST)	GLONASS Time (GLONASST)	BeiDou Time (BDT)	Galileo System Time (GST)

As we can see from **Table 8**, each GNSS uses its own reference frame so that the calculated receiver's position can have a ground reference. Furthermore, each GNSS uses its own reference time so that its three segments (Space, Control and User Segments) are time synchronized, and the time of arrival of the GNSS signals propagation can be measured [45].

4.1.4 GNSS PNT Performance

Table 9 summarizes the initial target PNT Performance of each GNSS for open service:

Table 9: GNSS Positioning and Timing Accuracy Performance

Parameter	GPS	GLONASS	BDS	Galileo
Positioning Accuracy	User Range Error (URE) ≤0.643 m (95% probability)	Horizontal 28 m and Vertical 60 m (95% probability)	10 m (95% probability)	Horizontal 15 m (E1) and 4 m (E1-E5b) and Vertical 35 m (E1) and 8 m (E1-E5b) (95% probability)
Navigation Accuracy	User Range Rate Error (URRE) ≤0.006 m/s (95% probability)	Velocity accuracy of 15 cm/s	Velocity accuracy of 0.2 m/s	*
Timing Accuracy	≤30 ns (95% of the time)	20 ns (95% probability)	20 ns	30 ns (with reference to UTC) (E1-E5b) (95% probability)

* Information not available.

As we can see from **Table 9**, all the GNSS have good target performance concerning the accuracy of the provided PNT services. It must be mentioned that information about velocity measurement accuracy of Galileo was not available. It is obvious that the PNT Accuracy for military use is higher than that for open service, due to national security reasons. Furthermore, SBAS improves each GNSS's PNT accuracy (Paragraph 3.2).

Nevertheless, the modernization efforts for each GNSS promise higher accuracy performance of these systems and, thus, even better PNT services provided to all the users, especially for some cases where civil GNSS applications request high PNT accuracy.

4.2 Technical comparison between the regional navigation satellite systems

Table 10 summarizes the parameters of the Space Segment of each regional navigation satellite system:

Table 10: Parameters of the regional navigation satellite systems' Space Segment

Parameter	IRNSS/NavIC		QZSS	
Coverage	India and a region of about 1,500 km around India		Asia and Oceania region with a focus on Japan	
Type of Orbit	GEO	IGSO	GEO	QZO
Inclination	0^o	29^o	0^o	$39^o – 47^o$
Number of satellites	3	4	1	3
Number of orbital planes	1	2	1	3

With the aid of **Table 10**, the comparison between the Space Segment of the two regional navigation satellite systems is the following:

✓ Both IRNSS/NavIC and QZSS constellations include satellites in GEO, because the two navigation satellite systems are regional and, thus, GEO satellites must cover all the time a specific area, India and a region of about 1,500 km around India, and Asia and Oceania region with a focus on Japan, respectively. Furthermore, satellites in inclined geosynchronous orbits are used for even better coverage of specific areas.

✓ The number of the satellites and the number of the orbital planes of the two regional navigation satellite system is different due to each system's design and coverage needs.

4.3 Critical analysis of the navigation satellite systems

After the comparison between the main parameters of the four GNSS and of the two regional navigation satellite systems in the previous paragraphs, and with the aid of the rest of their characteristics which have been presented in Chapter 3, a critical analysis of each system can now be presented:

➢ *GPS*:

GPS is the first ever developed GNSS. Initially, it was deployed only for military use and eventually has dual, military and civil use. The technique named Selective Availability, with which GPS was initially designed to operate, was a disadvantage for the system, because, actually, it was a degradation of the GPS signal when needed for national security reasons. On May 1, 2000, though, the United States Government decided the termination of the Selective Availability, thus the accuracy of the system was increased for the civil users.

GPS is a reliable and robust system, with high PNT accuracy performance, which is improved with the aid of the USA SBAS, the WAAS, in the territory of USA and by using the other SBAS in the corresponding areas, as well. Thus, numerous civil applications (Paragraph 2.8) are served by GPS at a global level.

Furthermore, the use of GPS in numerous weapon systems not only from the USA Armed Forces, but from other countries too, is one great advantage of the American GNSS: GPS offers significant services during the combat when very high PNT accuracy is needed and provides an important asset in the Armed Forces which use this global navigation satellite system.

➢ *GLONASS*:

GLONASS is the global navigation satellite system developed by the Russian Federation; this system is similar to GPS. GLONASS was initially developed exclusively for military use, like GPS, but, today, it is a dual system and it provides PNT services in both military and civil users.

Initially, the Russian GNSS was designed to use the FDMA technique for the transmission of its signals, fact that made the system non compatible with GPS, which uses the CDMA technique. This issue was solved, though, with the use of the CDMA technique in a different new band for the GLONASS signal transmission, as well. Thus, cooperation and interoperability with GPS could be achieved.

The target PNT accuracy performance for open service is improved due to the modernization of the system and with the aid of the Russian SBAS, the SDCM, thus, today, GLONASS can be characterized as a system with similar performance to that of GPS. Furthermore, the use of GLONASS from the Russian Armed Forces is crucial and gives them an asset especially to their targeting accuracy.

- *BDS*:

BDS, the Chinese GNSS, has a hybrid constellation consisting not only of satellites in MEO, but in orbits of higher altitudes (in IGSO and in GEO), as well. This fact gives BDS the advantage of a better performance in low-latitude areas by offering to the system better anti-shielding capabilities.

BDS today is a dual system, but initially was developed for military use only, like GPS and GLONASS. The Chinese GNSS was designed with a characteristic technique which makes it a two-way ranging system. With this technique (which has been presented in Paragraph 3.1.3) the position of the receiver (user) can be calculated by the Control Center of BDS, so that, security issues for the users of the system could arise, because they could, for instance, be attacked by malicious software.

The PNT performance of BDS is similar to that of GPS and GLONASS, and it is planned to be improved by 2035. BDS gives a great advantage to the Chinese Armed Forces which use this system, because their satellite navigation independence is reassured, which is crucial for national security reasons.

- *Galileo*:

Galileo is the only one of the four navigation satellite systems with no dual use: it was initially designed as a civil GNSS. Although it could be used for the military domain too, this effort is difficult due to the fact that Galileo is developed by the EU, thus 27 different countries should agree to the military use of the system. As a result of the non-dual use of Galileo, the Armed Forces of the member states of the EU must use other global navigation satellite systems to their weapon systems and not their own system.

The PNT performance of Galileo is similar to those of the other GNSSs and this system provides services of high accuracy to its users. Furthermore, its performance will be improved with the aid of EGNOS, as seen in Paragraph 3.2.1.

The great advantage of Galileo is that it already offers three types of services and it is planned to provide two more, so that its contribution to the security of the public is really significant.

- *IRNSS/NavIC*:

The regional navigation satellite system developed by India provides two types of PNT services to both authorized and civil users. Furthermore, this system covers India by reassuring navigation satellite independence to the country, as well as a region up to 1,500 km around India’s boundaries.

The positioning and timing performance of IRNSS/NavIC is better than 20 m and better than 50 ns, respectively. Thus, the Indian regional navigation satellite system has similar to the GNSS positioning and timing performance and provides high accurate services to its civil users.

- *QZSS*:

The Japanese regional navigation satellite system covers the Asia and the Oceania region with a focus on Japan. QZSS has the advantage of the usage of satellites in QZO in its constellation. Thus, in urban areas throughout Japan, where the access in the GPS signals many times is not possible because of, for instance, the high buildings of the area, QZSS's satellites in QZO offer better PNT services to these territories, especially when high accuracy is needed.

5. GNSS SECURITY AND DEFENSE APPLICATIONS

5.1 GNSS Military Security and Defense Applications

Navigation satellite systems, as already said, were initially developed for military purposes. Thus, GNSS military applications were and still are crucial for national security. It must be noticed that, conceptually, the term “security” includes the term “defense”, because security for every country comes first over everything else. So, the GNSS security and defense applications, practically refer to the GNSS security applications which are used in the Armed Forces. The most important of the GNSS military applications are the following [4,99,100]:

➢ *Target acquisition*: The determination of the accurate location of the enemies is crucial during a combat. Thus, the tracking of a potential target is necessary in order to declare it as hostile.

➢ *Aviation and maritime navigation*: The use of the navigation satellite systems in the aircrafts and the ships, gives them the opportunity to find their target in all weather, day or night, and even if the target is covered by dust.

➢ *Positioning and ground navigation*: The soldiers in unknown territories, using GNSS, can determine their exact position and be guided to the desired location with great accuracy and very quickly. For example, during the First Gulf War (1991), the Marines managed to orient themselves into the dessert using GPS portable receivers.

➢ *Missiles navigation*: Missiles using GNSS data can be guides to their targets with high accuracy. For example, cruise missiles, with the aid of GPS can find its target with an accuracy of approximately two meters. Thus, GPS-aided cruise missiles pose a significant threat to large fixed targets.

➢ *Communication with the control center* : The control center must know the exact position of all the soldiers, and this is possible with the use of the GNSS receiver that have each one of the military units.

➢ *Search and Rescue Missions*: In case of search and rescue of injured soldiers, it is crucial to reduce the response time. With the aid of the GNSS, the location of the soldiers can be calculated accurately and in short time.

➢ *Supply Missions*: During a supply mission, using navigation satellite systems, the vehicles can meet each other more quickly and with reduced risk.

It is obvious that the use of navigation satellite systems for military purposes gives great advantage to the countries. Nowadays, national security and defense depend largely on the PNT provided services. The Gulf War was the first war where a GNSS was used: GPS defined the superiority of the Unites States Army. Today, the Russo-Ukrainian Conflict is a typical example of the necessity of the use of GNSS during a combat, especially for target acquisition.

Figure 22 shows a portable defense GPS receiver [101]:

Figure 22: Portable defense GPS receiver (Source: [101])

5.2 GNSS Civil Security and Safety Applications

Today, the use of navigation satellite systems for civil purposes is crucial for many aspects of our everyday lives. The GNSS civil security (protection from intentional threats, e.g., terrorist attacks) and safety (protection from unintentional threats, e.g., natural disasters) applications affect infrastructures and civil sectors such as civil aviation, railways, transport of dangerous goods, search and rescue, and emergency warning services.

5.2.1 GNSS in Civil Aviation

GNSS is used in civil aviation to increase the safety of all the phases of flights globally [102]. PNT services provide to aircrafts shorter flight routes that equals to economy to the fuel [103] and improved landing during conditions of reduced visibility (such as fog or volcanic ash during a volcanic eruption) and in all weather. Furthermore, SBAS, which are discussed in Paragraph 3.2, aid civil aviation by augmenting GNSS signals in areas such as urban territories, where the line-of-sight with four navigational satellites simultaneously is difficult or even impossible.

The International Civil Aviation Organization (ICAO) incorporated in 1999 Standards and Recommended Practices (SARPS) for the services provided by GNSS to civil aviation on global basis [104]. Furthermore, the use of GNSS in civil aviation requires a renewal to regulation, to aircraft operation and definitely to flight training of the pilots, which is necessary so that pilots can operate the GNSS equipment [105].

Figure 23 shows the architecture of GNSS and SBAS aiding civil aviation [106].

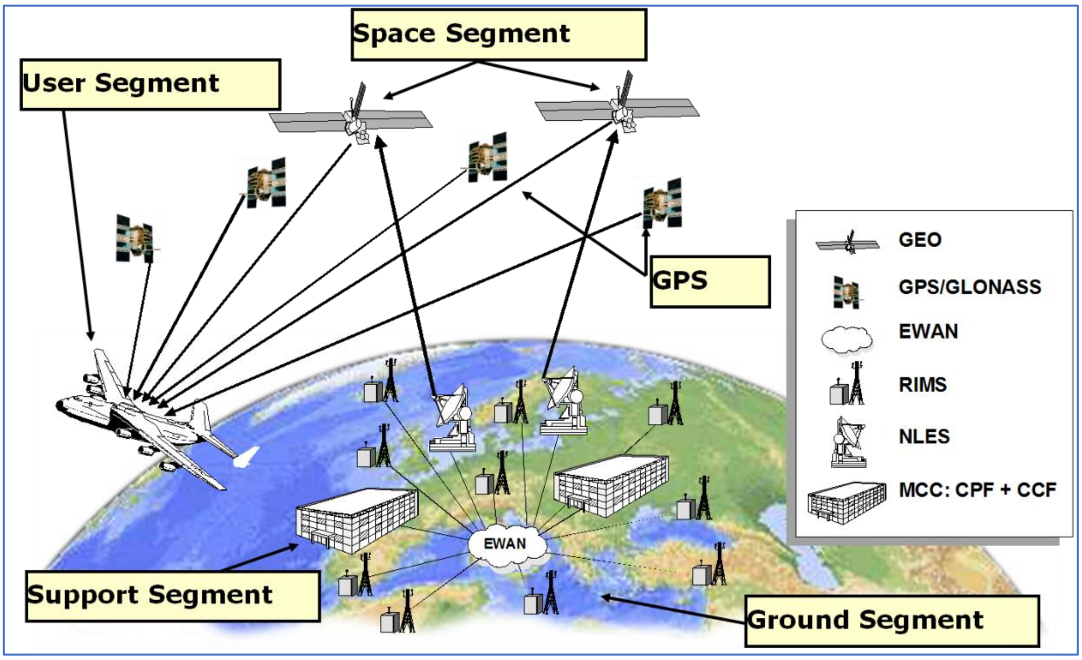

Figure 23: GNSS and SBAS Architecture aiding civil aviation (Source: [106])

5.2.2 GNSS in Railways

The use of navigation satellite systems in railways has many advantages: reducing accidents and delays, improving rail security and safety, and increasing railways operation are some of them [107]. GNSS provide accurate positioning and velocity of each train, so collisions between them can be prevented. Furthermore, navigation satellite systems synchronize the time of the rail communication systems between the trains and the rail stations, and they also provide accurate information on arrival times to the stations.

5.2.3 GNSS in Transport of Dangerous Materials

In the transport sector of Dangerous Materials, GNSS provide tracking and tracing services necessary for security and safety [108]. During the transport of dangerous materials, PNT services can determine the position and the velocity of the truck at any time of the route. Furthermore, in case of terrorism, the truck can be located with great accuracy with the use of the global navigation satellite systems.

5.2.4 GNSS in Search and Rescue

The contribution of GNSS in search and rescue is crucial. With navigation satellite systems lost or injured persons can be located accurately and very quickly via their GNSS receivers. Furthermore, in case of natural disasters such as earthquakes or floodings, the search and rescue teams, using GNSS combined with other technologies, can create maps of the disaster areas, so that they carry out the rescue operations [109].

5.2.5 GNSS in Emergency Warning Services

Another crucial civil security and safety GNSS application is in Emergency Warning Services. In an emergency crisis, navigation satellite systems can provide very fast and efficient response [110]. This GNSS application includes all types of hazards, such as earthquakes, tsunamis, floodings, forest fires, even terrorist attacks [111]. Furthermore, GNSS signals combined with mobile phone networks provide emergency communications for warning about hazards in a particular area, such as toxic gas, or for emergency evacuation because of a forest fire. The European 112-emergency number is an example of GNSS emergency warning service.

➢ The European 112-emergency phone number:

The phone number 112 is the EU's emergency number, which is available all over the European Union area, and it is free of charge (**Figure 24**) [112]. So far, in a 112 call, the information of the caller's location was provided by a cellular network town on the coverage area (of the caller's) with an average accuracy of two to ten kilometers; the use of GNSS signals though, can provide a location accuracy of a few meters, which is vital for the caller [113]. Specifically, the Advanced Mobile Location (AML) protocol for the 112 service uses the data transmitted by Galileo and the caller's smartphone to determine the caller's location with great accuracy. Then, AML transmits the coordinates of the caller's location to a Public Safety Answering Point (PSAP) and, finally, the rescuers know the exact location of the caller.

Figure 24: 112 - The EU's Emergency Number (Source: [112])

5.3 GNSS in Unmanned Aerial Vehicle (UAV)

Unmanned Aerial Vehicle (UAV) or “Drone” is a small aircraft which fly autonomously without a pilot [114]. The UAVs’ main navigation system is GNSS. UAVs can fly either single or in swarms. It must be noticed that in the case of UAV swarms, navigation information accuracy is crucial to avoid collision between them [115]. With the aid of GNSS, the applications of UAVs in security and defense as well as in civil security and safety are of great importance.

5.3.1 Military security and defense applications of UAVs

The main characteristic of UAVs is that they fly without a pilot and consequently their low cost, which gives them a great advantage. Thus, the use of UAVs for military purposes with the aid of GNSS has numerous applications. Today, many countries include in their Armed Forces the use of UAVs in security and defense. In **Figure 25** is shown the US Army’s MQ-9 Reaper UAV [116].

Figure 25: The US Army's MQ-9 Reaper UAV (Source: [116])

Military UAVs can be armed or unarmed. Armed forces operate UAVs of all sizes and weights, but most of the armed ones are much larger than the usual civil UAVs [117]. The most important military applications of the UAVs are the following [103]:

- *Intelligence Surveillance and Reconnaissance (ISR) Missions*:

During a combat, the defender’s ISR Missions are very important to track and detect the enemy location along potential targets. Accurate positioning is necessary, so UAVs, which can fly fast and close to the ground and are navigated by GNSS, are ideal for ISR missions.

➢ *Search and Rescue Missions*:

UAVs in search and rescue missions for injured soldiers are crucial. UAVs can reach the specific area and locate the soldiers much faster than people or other aircrafts and helicopters, and GNSS give the asset to UAVs for accurate positioning. Furthermore, in some cases, UAVs are the only solution for this kind of detections because of the specific territory.

➢ *Border Security*:

UAVs are a great asset in border monitoring; with the aid of GNSS and equipped with thermal detection cameras, they can detect movement of people trying to cross illegally the country's border as well as other irregular activities, especially in territories with dense vegetation [118].

➢ *Detection of chemical and nuclear substances*:

In some cases, where a chemical or even nuclear substance release has occurred, it is really dangerous for soldiers to approach the specific area. UAVs equipped with scientific instruments such as Geiger-Müller Counter are ideal for such missions.

5.3.2 Civil security and safety applications of UAVs

Civil applications of UAVs are very important for civil security and safety. Their low cost and their ability to reach inaccessible for people areas make UAVs valuable for crisis management, such as cases where people are in danger or man-made and natural disasters. The most critical civil applications of UAVs are the following:

➢ *Search and Rescue (SAR)* [114]:

The use of civil UAVs for search and rescue is for many cases the unique solution, especially in areas where it is very difficult for the rescuers to reach. Injured climbers in mountains or lost people in areas with very dense vegetation can be detected quickly and accurately with the aid of UAVs and the GNSS navigation. Furthermore, UAVs can reach people who are in danger in the sea very fast and throw life preservers to them.

➢ *Disaster Management* [119]:

During man-made disasters (such as terrorist attacks) and natural disasters (such as floodings, earthquakes or tsunamis), most of the times it is very difficult or even impossible to reach the affected areas. UAVs can fly close to the ground and, using the GNSS signal, can approach areas where it is possible to find survivors. Furthermore, in disaster management, UAVs can provide information to the authorities about the extent of the damage with high accuracy.

- *Delivery of Medical Products* [117]:

Civil UAVs are really valuable in medical emergencies. In cases where the delivery of medical products is vital, UAVs have been proven as the unique solution. At inaccessible or remote places, UAVs can deliver medical products fast and with safety. Furthermore, in countries of Africa such as the Republic of Rwanda, there is a national network of medical UAVs which deliver medical products such as blood to remote areas of the country.

Figure 26 shows a civil UAV delivering medical products [120].

Figure 26: Civil UAV delivering medical products (Source: [120])

6. INTENTIONAL THREATS AGAINST GNSS

In this Chapter, the intentional threats against GNSS will be discussed. The vulnerability of GNSS to these threats is an issue which can cause severe problems to the PNT services provided by the navigation satellite systems. Thus, the detection and the mitigation of intentional threats against GNSS are of great importance.

6.1 GNSS Interference

The power of the GNSS signal is low, and it is comparable to a 60W light bulb [121]. Furthermore, it is broadcasted by navigation satellites wirelessly from approximately 20,000 km away from Earth's surface. Thus, the GNSS signal is vulnerable to *Interference*, a phenomenon where radio signals can disrupt the GNSS signals, so that the provided by the navigation satellite systems PNT services can be reduced or even be discontinued. GNSS Interference can be either *unintentional* or *intentional*:

➢ Intentional interference is defined as noise caused unintentionally by artificial radiation (for example, radiation from industrial installations) or by natural reasons such as ionospheric effect in the GNSS signal propagation (as seen in Paragraph 2.6).

➢ *Intentional interference* occurs when transmitted radio signals disrupt the GNSS signals purposely and cause problems in PNT services. Intentional interference is referred to as *"intentional threats against GNSS"* and it is distinguished in *GNSS Jamming* and *GNSS Spoofing*.

Table 11 summarizes the kinds and types of GNSS interference:

Table 11: GNSS Interference

GNSS INTERFERENCE				
Kind of Interference	Unintentional Interference		Intentional Interference	
Type of Interference	Artificial Radiation	Natural Reasons	Jamming	Spoofing

6.1.1 GNSS Jamming

GNSS Jamming [121,23] is defined as the emission of radio signals which have enough power to prevent a GNSS receiver from receiving a GNSS signal. Practically, that means that the GNSS receiver has reduced PNT services or even total outage of them. These radio signals, the jamming signals, can be generated by low-cost devices called "GNSS jammers".

GNSS jammers can be found on the commercial market or even built using instructions from the Internet. Small GNSS jammers have a power between 1 and 10 W, and are lightweight. GNSS jammers of higher power (up to KW) are more expensive and vulnerable and can be rapidly located.

The size of the area affected by the jamming attack depends on the power of the jammer and the strength of the navigation satellite signal. For instance, a jammer which can be found on the commercial market can affect a receiver even from 150 - 200 km away from it.

Several algorithms and techniques have been developed for the detection and the mitigation of jamming attacks, and they will be discussed in Paragraph 6.2.

Figure 27 shows an attack of a jammer (attacker) which emits jamming signals (the red ones) and the GNSS receiver (the ship) cannot receive the GNSS signals (the blue ones) [122].

Figure 27: GNSS Jamming (Source: [122])

6.1.2 GNSS Spoofing

GNSS Spoofing [121,23] is the transmission of fake radio signals to the receiver. These signals mimic the actual GNSS signals. Thus, the GNSS user receives the spoofed signals and, as a result, fake PNT services are provided to him. Spoofing is technically much more pretentious than jamming because the spoofed signal must be similar to the GNSS signal. GNSS military signals, being encrypted, are more protected from spoofing than the civil ones. Nevertheless, GNSS spoofing could also become dangerous for military and civil users.

The spoofing devices or “GNSS spoofers” can be found in the commercial market like the jammers, but they are technically more complex and more expensive than the jammers.

In **Figure 28** is shown an attack from a spoofer (attacker) which transmits fake signals to the receiver, thus false PNT services are provided to the ship [122].

Figure 28: GNSS Spoofing (Source: [122])

❖ It must be noticed that if the power of the spoofed signal is higher than the power of the true GNSS signal, then the receiver will be jammed and not spoofed. Furthermore, if the power is lower, then the spoofed signal will be ignored by the receiver. Thus, spoofing requires that the power of the false signal is nearly the same as the true signal’s power.

❖ The two types of malicious devices, GNSS Jammers and Spoofers, can be ground-based, for instance on a hill, so they have the advantage of being close to the GNSS receivers which will be attacked [23]. These devices can also be placed on an aircraft, so that they could affect many GNSS receivers. Furthermore, ships can be equipped by jammers and spoofers, so attacks can be made to other ships and vessels. GNSS Jammers and Spoofers are used for attacking the UAVs as well.

6.2 Intentional Threats against GNSS: Detection and Mitigation

Intentional Threats against GNSS, that is GNSS Jamming and Spoofing, can cause many problems in PNT services provided to the users. Especially in military use, jamming and spoofing could be fatal during a combat. Thus, it is particularly important to detect them in order to mitigate them and the users be protected as much as possible.

6.2.1 GNSS Jamming and Spoofing Detection

The detection of GNSS intentional interference (jamming and spoofing) can be done with several algorithms and techniques. The efficiency of these methods depends on the type of the interference [121].

➢ *GNSS Jamming Detection*:

GNSS jamming detection can be done with various methods which are based on different principles. Numerous algorithms and techniques are currently under research. The most important categories of these methods are the following [123]:

- Algorithms based on direction of arrival estimation:

The characteristics of these methods are that additional antennas, more complex hardware and high computational power are needed.

- Methods based on statistical analysis of the received signal:

These methods are based on the difference between the Probability Distribution Functions (PDF) of the received signal with and without jamming. The change in the PDF of the received signal power is used for GNSS jamming detection.

- Signal Quality Measurement (SQM) methods:

These are accurate methods in GNSS jamming detection, but they are receiver-hardware dependent.

- Subspace methods:

This is an important category of jamming detection methods. Their advantage is that these methods are accurate and sensitive. On the other hand, they are computationally heavy, so they are not efficient in real time applications.

- Methods based on Random Matrix Theory (RMT):

These methods are used to analyze the asymptotic and limited behavior of the signal and its related eigen-values/vector. Various of these methods which are not computationally heavy and which can be used as an early warning stage in real time applications are currently under research.

➢ *GNSS Spoofing Detection*:

Different algorithms and techniques have been proposed for GNSS spoofing detection. The most important of these methods are the following [124]:

- Methods Based on the Signal Power Monitoring:

These methods are based on the monitoring of the changes in the received signal power, which are not related to natural reasons such as ionospheric variations. These changes can indicate the presence of a spoofing signal.

- Spatial Processing methods:

One of the characteristics of the spoofing signals is that these signals are transmitted from the same antenna while the authentic GNSS signals are transmitted from different satellites with different directions. Thus, using the Spatial Processing methods, the spatial signature of the received signals can be estimated and then the spatially correlated signals can be discriminated.

- Code and Phase Rates Consistency Check methods:

In the authentic GNSS signals, the Doppler frequency and the code delay rate, they are both affected by the relative movement between the GNSS satellite and the receiver, thus they are consistent. The spoofing signal can be detected from the fact that in the case of a spoofing signal, there is not a consistency between the Doppler frequency and the code delay rate.

- Received Ephemeris Consistency Check methods:

The authentic GNSS navigation message which is transmitted from each satellite of the system includes ephemeris information about the position of the other satellites of the constellation. Therefore, a spoofing attack can be detected by checking whether there is an inconsistency among these ephemeris data.

- GNSS Clock Consistency Check methods:

The authentic GNSS navigation message of each PRN signal includes the GNSS clock information, which is obtained from the system's satellites, and should be consistent. Thus, if there is an inconsistency between the GNSS time extracted from different satellites of the constellation, this could indicate a spoofing attack.

6.2.2 GNSS Jamming and Spoofing Mitigation

For achieving the mitigation of GNSS jamming and spoofing attacks, various methods are used. The research in this domain is advancing and more efficient algorithms and techniques are developed in order to protect GNSS from the malicious attacks.

➢ *GNSS Jamming Mitigation* [125]:

There are several methods for GNSS Jamming Mitigation (or “Anti-Jamming Methods”); the most important of them are the following:

- The Interference Cancellation (IC) Principle methods:

In this method, after detecting the interference, the parameters which characterize the interfering signal are estimated from the available data. Then, the reconstructed interference is subtracted from the data and a clean signal version is used eventually from the receiver.

- Robust Estimation methods:

These methods are based in the theory of robust statistics. In the Robust Estimation methods, the receiver produces reasonable results even in the presence of interference and it does not try to estimate the jamming signal, like the IC Principle methods do. It must be noticed that the term “robust” is used as a mathematical property of a system whose assessment can be done with the usage of strict criteria.

- Time Domain (TD) methods:

These methods belong to an advanced class of GNSS jamming mitigation techniques. In these methods, it is not required a preliminary transformation to bring the input samples in a different domain; the momentary frequency of the jamming signal is continuously estimated and the region of the spectrum which is occupied by the jamming signal is removed through filtering.

- Robust Time Domain (RTD) methods:

The usage of the Zero-Memory Non-Linear (ZMNL) functions in the TD techniques is a new class of TD approaches. In these methods, the input samples are projected into the TD, then the samples are processed and used to reconstruct a clean version of the time domain input signal.

➢ *GNSS Spoofing Mitigation* [124]:

The methods for GNSS Spoofing Mitigation (or "Anti-Spoofing Methods") neutralize the detected spoofing signals and help the receiver to retrieve the correct PNT calculations. The most important of the GNSS Anti-Spoofing Methods are the following:

- Vestigial Signal Detection methods:

In these methods, a vestige of the authentic GNSS signal which remains is used for spoofing mitigation. The disadvantage of the Vestigial Signal Detection methods is that, as this technique requires additional tracking channels so that the two signals, the authentic and the spoofing, are tracked, an increased hardware and processing complexity of the receivers is needed.

- Multiantenna Beam Forming and Null Steering methods:

These methods use a multi-antenna receiver which first detect the direction of the spoofing signal and then, it steers a null toward the source of the spoofing signal. Thus, the spoofing signal is mitigated and the receiver is eventually safe.

- Receiver Autonomous Integrity Monitoring (RAIM) methods:

The GNSS receiver pseudorange measurements which come from the spoofing signals might be inconsistent. The Receiver Autonomous Integrity Monitoring (RAIM) methods are used from most of the receivers in order to detect and then reject the "extreme" measurements of the spoofing signals. The disadvantage of these methods, though, is that if the spoofed pseudorange measurements are in majority, then the RAIM methods could reject not only the false but the authentic measurements, as well.

❖ Apart from the methods described above, another research area for methods for GNSS jamming and spoofing mitigation, which is under research, includes the Machine Learning (ML) and the Artificial Intelligence (AI) techniques. These two algorithms, by processing a huge amount of data, can then deliver remote site analysis and automated detection of potential GNSS jamming and spoofing attacks [126].

Figure 29 shows a simulation of Detection and Mitigation of GPS jamming and spoofing [127].

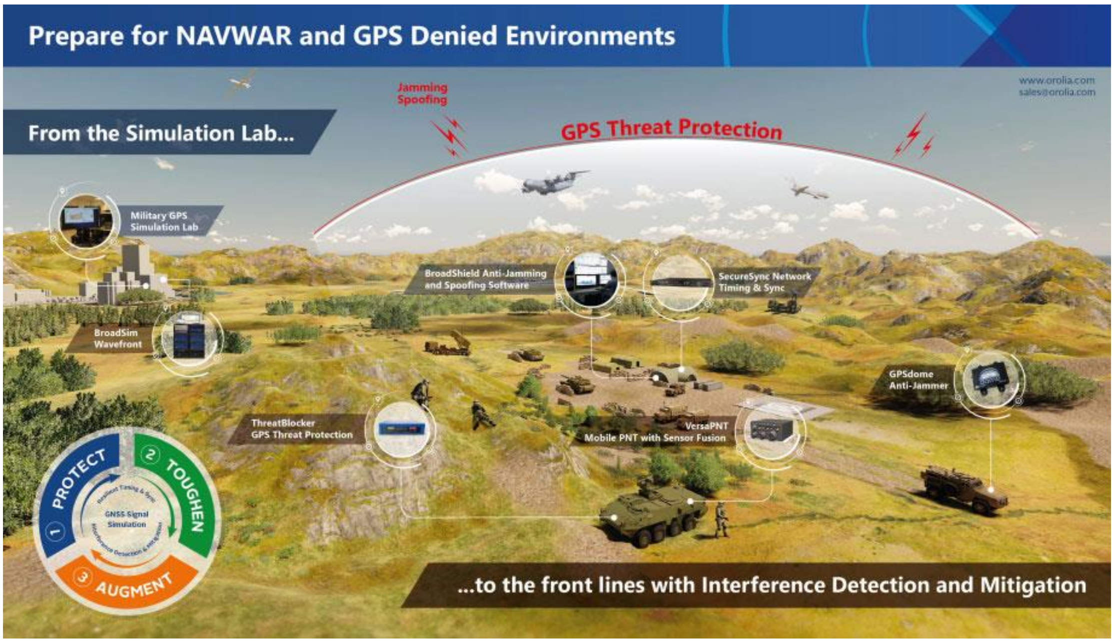

Figure 29: Simulation of Detection and Mitigation of GPS Jamming and Spoofing (Source: [127])

6.3 Incidents of Intentional Threats against GNSS

Intentional threats against GNSS have been observed several times. The most characteristic incidents are the following:

- During the Iraq War in 2003, the Iraqi forces used GPS jammers, but the United States forces detected and destroyed them rapidly [23].

- Beginning in February 2016 and using Automatic Identification System (AIS) ship location data, 9,883 instances of GNSS spoofing were identified, affecting 1,311 commercial vessels. These incidents of GNSS intentional interference appear to have originated from more of ten locations in Russia and Russian-controlled areas in Crimea and Syria [128].

- After the conflict in Crimea in 2014, the Russian military in 2016 bought GPS jammers for placing them on cell phone towers, so that they could cause problems to PNT services provided by GPS in enemy cruise missiles and UAVs [129]. Since then, numerous intentional GPS interference incidents have affected GPS receivers in Eastern Ukraine [130].

- In June 2017, there was an incident of GPS spoofing that affected over 20 vessels in Black Sea [131]. The false GPS signal occurred an error in the positioning of the vessels of about 46 km [130].

- Since the beginning of 2018, possible GPS jamming was observed in the Eastern Mediterranean near Cyprus and in the entrance to the Suez Canal [132].

- In 2019, were observed 10,000 separate GPS spoofing incidents which had been conducted by Russia, as the non-profit C4ADS documented [133].

- In August 2021, an incident of GNSS interference to commercial shipping in the Mediterranean was reported. The interruptions to the GNSS signals and thus to the PNT services were temporary [134].

6.4 Intentional Threats against GNSS in the Russo-Ukrainian Conflict

The Russo-Ukrainian Conflict began on February 24th, 2022. In February 2022 and just before the beginning of the conflict, was detected interference in the GPS signal along the Ukraine-Belarus border [133].

US Space Force claimed that, from the beginning of the conflict, the Russians attacked the GPS signals, so the Ukrainians could not use GPS [135]. This could be a significant disadvantage for Ukraine, because the use of GNSS is valuable during war. The Ukrainian UAVs though, are not affected by the Russian GPS jammers and spoofers, because they attack targets very quickly, so that the Russian GPS interference systems do not have the time to detect them [130].

The civil GPS signal is more vulnerable to interference than the military one. Thus, during the Russo-Ukrainian Conflict, in March 2022, there were incidents of interference that affected mainly civil aviation and forced the aircrafts even to change their destination in some cases [130]. Furthermore, on March 17, 2022, the European Union Aviation Safety Agency (EASA) released a safety information bulletin entitled "Global Navigation Satellite System Outage Leading to Navigation / Surveillance Degradation" [122], warning of the increased probability of GNSS outages related to the Russo-Ukrainian Conflict [136]. According to EASA, the four areas where GNSS interference has been detected are: Kaliningrad Region surrounding the Baltic Sea, Eastern Finland, Black Sea, and Eastern Mediterranean (shown with red circles in **Figure 30**) [122].

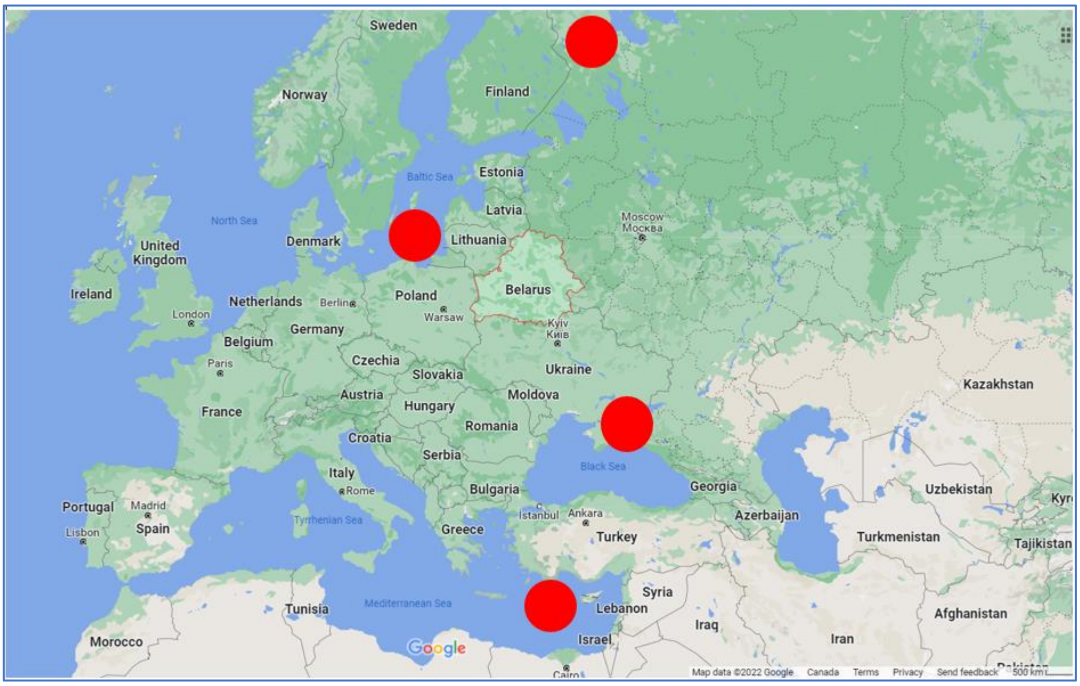

Figure 30: Map with the regions with detected GNSS interference (17/03/2022) (Source: [122])

7. CONCLUSIONS

The first navigation satellite systems were developed initially for military purposes. And this, because since the 1960s, USA as well as the former Soviet Union had realized how valuable these systems could be during a military combat: the accuracy of targeting and positioning that these systems could provide to their Armed Forces could not be compared to the other already used at that time systems.

With time, the first developed navigation satellite systems were evolved to the current GNSS. Many countries began using the USA's GPS, but some of them, due to national security reasons, decided to develop their own global or regionalan using the USA's GPS. However, some of them decided to develop their own global or regional navigation satellite systems due to national security reasons. Thus, today, there are four fully operational GNSS with global coverage and two regional systems which cover only specific regions. Furthermore, augmentation to the GNSS signal systems (named SBAS) have been developed.

The satellites of the GNSS are located in MEO, thus they confront the space environment's and the space weather's hazards. Therefore, suitable and reinforced shielding of the navigation satellites is necessary in order to compensate these threats. Additionally, there are sources of errors in these systems due to natural reasons, which affect their performance. Global models are under research and must be further developed to mitigate the errors.

A technical comparison between the navigation satellite systems shows that all of them are reliable systems that provide their users PNT services of high accuracy. Nevertheless, modernization of these systems is necessary for the improvement of the provided services. It is obvious, though, that each system is first of all suitable for the area of the corresponding country which has developed that system.

The three of the four GNSS (the American GPS, the Russian GLONASS and the Chinese BDS) have nowadays dual use, military and civil. Only the European Galileo was initially designed and developed exclusively as a civil navigation satellite system. All the global as well as the regional navigation satellite systems have numerous applications in people's everyday life. These systems are used in almost all the aspects of humans' daily routine. For instance, all the smartphones are equipped with GNSS receivers. PNT services which are provided from GNSS are available to public 24/7, in all weather and free of charge.

One of the most critical assets of the navigation satellite systems is their role in security and defense (in military use) and in security and safety (in civil use). The contribution of these systems in national security is out of question: their aid to the border monitoring or during a military combat is unique in many cases. The accuracy of PNT services that navigation satellite systems provide is unique and can save human lives, given that injured soldiers can be tracked very fast, for instance. In the civil sector, these systems save many lives every day. During a crisis situation, PNT services provided by the navigation satellite systems, contribute to the estimation of the situation and to the decision making. Lost and injured people can be tracked really fast even at the most difficult territories, such as in mountains, and be saved.

The GNSS signal is a low power signal, so it is vulnerable to intentional interference. Therefore, the military GNSS signal is more resistant to intentional threats against it than the civil one. The two kinds of intentional interference, GNSS jamming and GNSS spoofing, can affect the signal which is transmitted by the navigation satellites and cause severe problems to the PNT provided services. Many techniques for detecting and mitigating jamming and spoofing attacks are under research to protect the GNSS signals from the effect of the malicious devices because the shielding against the malicious attacks is crucial, as false or intentionally interrupted PNT services could cost even human lives.

It must be noticed that several incidents of GNSS malfunction due to intentional interference have been detected during the years. Currently, GPS jamming and spoofing attacks are observed, which are related to the Russo-Ukrainian Conflict.

It is undoubtable that navigation satellite systems are nowadays completely connected to people’s lives. Our national security depends largely on GNSS and regional navigation satellite systems. Thus, further research must be done, concerning their shielding against natural or intentional threats, in order to these systems provide even better and more accurate services. Furthermore, authorities, rescuers, pilots etc. must be trained in operating the GNSS equipment, so that the navigation satellite systems can be a valuable and decisive assistant in crisis.

ABBREVIATIONS - ACRONYMS

AI	Artificial Intelligence
AIS	Automatic Identification System
AML	Advanced Mobile Location
APL	Applied Physics Laboratory
BDC	BeiDou Coordinate System
BDS	BeiDou Navigation Satellite System
BDT	BeiDou Time
BKZS	Bölgesel Konumlama ve Zamanlama Sistemi
BM	Broadcast Message
C/A	Coarse Acquisition
CDMA	Code Division Multiple Access
CS	Commercial Service
DGNSS	Differential Global Navigation Satellite System
DoD	Department of Defense
DoT	Department of Transportation
EASA	European Union Aviation Safety Agency
EDAS	EGNOS Data Access Service
EGNOS	European Geostationary Navigation Overlay Service
EGNOS OS	EGNOS Open Service
EGNOS SoL	EGNOS Safety-of-Life Service
ESA	European Space Agency
EU	European Union
EUSPA	European Union Agency for the Space Programme
FAA	Federal Aviation Administration
FDMA	Frequency Division Multiple Access
GAGAN	GPS-Aided GEO Augmented Navigation System
GCC	Galileo Control Center
GEO	Geostationary Orbit
GLONASS	Globalnaya Navigatsionnaya Sputnikovaya Sistema
GLONASS	GLONASS Time
GNSS	Global Navigation Satellite System
GPS	Global Positioning System

GPST	GPS Time
GST	Galileo System Time
GTRF	Galileo Terrestrial Reference Frame
IC	Interference Cancellation
ICAO	International Civil Aviation Organization
ICG	International Committee on Global Navigation Satellite Systems
IGSO	Inclined Geosynchronous Orbit
IRNSS/NavIC	Indian Regional Navigation Satellite System / Navigation with Indian Constellation (IRNSS/NavIC)
ISL	Inter-Satellite Link
ISR	Intelligence Surveillance and Reconnaissance
ITU	International Telecommunication Union
JDAM	Joint Direct Attack Munition
KPS	Korean Positioning System
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
ML	Machine Learning
MSAS	MTSAT Satellite Based Augmentation Navigation System
MTSAT	Multifunctional Transport Satellite
NATO	North Atlantic Treaty Organization
NAVSTAR/GPS	Navigation Satellite Timing And Ranging / Global Positioning System
NNSS	United States Navy Navigation Satellite System
NOAA	National Oceanic and Atmospheric Administration
OS	Open Service
PDD	Presidential Decision Document
PDF	Probability Distribution Function
PNT	Positioning, Navigation and Timing
PPS	Precise Positioning Service
PRN	Pseudo-Random Noise
PRS	Public Regulated Service
PSAP	Public Safety Answering Point
PZ-90	Parametri Zemli 1990
QZO	Quasi-Zenith Orbit
QZSS	Quasi-Zenith Satellite System

RAIM	Receiver Autonomous Integrity Monitoring
RMT	Random Matrix Theory
RNSS	Radio Navigation Satellite Service
RS	Restricted Service
RTD	Robust Time Domain
SA	Selective Availability
SAR	Search and Rescue Service
SARPS	Standards and Recommended Practices
SBAS	Satellite Based Augmentation System
SDCM	System for Differential Corrections and Monitoring
SLR	Satellite Laser Ranging Station
SLR's	Small, Lightweight GPS Receivers ("Sluggers")
SoL	Safety of Life Service
SPS	Standard Positioning Service
SQM	Signal Quality Measurement
TD	Time Domain
TT&C	Telemetry, Tracking and Command Center
UAV	Unmanned Aerial Vehicle
URE	User Range Error
URRE	User Range Rate Error
USA	United States of America
UTC	Coordinated Universal Time
WAAS	Wide Area Augmentation System
WGS-84	World Geodetic System 1984
ZMNL	Zero-Memory Non-Linear
2SOPS	2nd Space Operations Squadron
19SOPS	19th Space Operations Squadron

REFERENCES

[1] Nicolas Peter, Nadia Afrin, Gérardine Goh, and Ed Chester, Space technology, sustainable development and community applications: Internet as a facilitator, *Pergamon Acta Astronautica*, 59, 2006, pp.445-451.

[2] Geospatial World, "How many satellites are orbiting the Earth in 2021?", By Nibedita Mohanta, 05/28/2021, https://www.geospatialworld.net/blogs/how-many-satellites-are-orbiting-the-earth-in-2021/ [Accessed 1/6/22].

[3] Joseph N. Pelton, Scott Madry, and Sergio Camacho-Lara, *Handbook of Satellite Applications*, Springer International Publishing, 2017.

[4] Alexandros Kolovos, *The Daedalus Sky: Military Uses of Space*, Occasional Paper No. 6, The Greek Institute for International and Strategic Studies, Athens, April 1993.

[5] G. Krüger, R. Springer, and W. Lechner, Global Navigation Satellite Systems (GNSS), *Elsevier Computers and Electronics in Agriculture*, 11, 1994, pp.3-21.

[6] U.S. Department of Transportation, "What is Positioning, Navigation and Timing (PNT)?", Updated: Tuesday, June 13, 2017, https://www7.transportation.gov/pnt/what-positioning-navigation-and-timing-pnt [Accessed 1/6/22].

[7] ROSCOSMOS, "About GLONASS", https://www.glonass-iac.ru/en/about_glonass/ [Accessed 1/6/22].

[8] GPS WORLD, "Part 1: The Origins of GPS, and the Pioneers Who Launched the System, Part 1 of a Two-Part Story", *By Bradford W. Parkinson and Stephen T. Powers, with Gaylord Green, Hugo Fruehauf, Brock Strom, Steve Gilbert, Walt Melton, Bill Huston, Ed Martin, James Spilker, Fran Natali, Joe Strada, Burt Glazer, Dick Schwartz, Tom Stansell, and others,* May 1, 2010, https://www.gpsworld.com/origins-gps-part-1/ [Accessed 1/6/22].

[9] eoPortal – Powered by ESA, Satellite Missions Catalogue, "Transit", June 18, 2012, https://www.eoportal.org/satellite-missions/transit#tip-transit-improvement-program [Accessed 1/6/22].

[10] Anil K. Maini, and Varsha Agrawal, *Satellite Technology - Principles and Applications*, A John Wiley and Sons, Ltd., Publication, 2011.

[11] *SaPPart White Paper - Better use of Global Satellite Systems for safer and greener transport*, IFSTTAR, 2015. Available at: https://www.researchgate.net/publication/305724028_Better_use_of_Global_Satellite_Systems_for_Safer_and_Greener_Transport.

[12] GISGeography, "How GPS Receivers Work – Trilateration vs Triangulation", Last Updated: May 31, 2022, https://gisgeography.com/trilateration-triangulation-gps/ [Accessed 12/6/22].

[13] ESA Navipedia, "Reference Frames in GNSS", 2011, Last edited on 23 February 2021, https://gssc.esa.int/navipedia/index.php/Reference_Frames_in_GNSS [Accessed 5/6/22].

[14] Salvatore Gaglione, How does a GNSS receiver estimate velocity?, *Inside GNSS - GNSS Solutions*, March / April 2015, p. 38-41.

[15] Time and Date, "How Does an Atomic Clock Work?", By Konstantin Bikos, https://www.timeanddate.com/time/how-do-atomic-clocks-work.html [Accessed 1/6/22].

[16] Geospatial World, "How GNSS signals work within specific frequency bands", By Anusuya Datta 11/25/2019, https://www.geospatialworld.net/blogs/gnss-frequency-bands-for-constellations/ [Accessed 1/6/22].

[17] ITU, "About International Telecommunication Union (ITU)", https://www.itu.int/en/about/Pages/default.aspx [Accessed 5/6/22].

[18] U.S. Department of Transportation, "What is Radio Spectrum?", Last updated: Thursday, September 21, 2017, https://www.transportation.gov/pnt/what-radio-spectrum [Accessed 5/6/22].

[19] ESA Navipedia, "GNSS signal", 2011, Last edited on 30 May 2014, https://gssc.esa.int/navipedia/index.php/GNSS_signal [Accessed 5/6/22].

[20] Demosthenes Vouyioukas, ed., *Satellite Communications - Technologies, Systems and Applications*, Hellenic Academic Libraries Link, Kallipos, 2015.

[21] ESA, "About satellite navigation", https://www.esa.int/Applications/Navigation/About_satellite_navigation2 [Accessed 5/6/22].

[22] Jerry Jon Sellers, ed., With Contributions by: William J. Astore, Robert B. Giffen, and Wiley J. Larsen, *Understanding Space - An Introduction to Astronautics*, McGraw-Hill, 2004.

[23] David Wright, Laura Grego, and Lisbeth Gronlund, *The Physics of Space Security - A Reference Manual*, American Academy of Arts and Sciences, 2005.

[24] NASA, "Radiation Belts with Satellites", Feb 18, 2013, Last Updated: Aug 7, 2017, https://www.nasa.gov/mission_pages/sunearth/news/gallery/20130228-radiationbelts.html [Accessed 5/6/22].

[25] Space Weather Prediction Center, National Oceanic and Atmospheric Administration, "NOAA Space Weather Scales", https://www.swpc.noaa.gov/noaa-scales-explanation [Accessed 5/6/22].

[26] Space Weather Prediction Center, National Oceanic and Atmospheric Administration, "Alerts, Watches and Warnings", https://www.swpc.noaa.gov/products/alerts-watches-and-warnings [Accessed 5/6/22].

[27] Space Weather Prediction Center, National Oceanic and Atmospheric Administration, "Space Weather Phenomena", https://www.swpc.noaa.gov/phenomena [Accessed 5/6/22].

[28] Paul B. Larsen, Issues relating to civilian and military dual uses of GNSS, *Elsevier Space Policy*, 17, 2001, pp.111-119.

[29] EUSPA, European Union Agency for the Space Programme, "What is GNSS?", Updated: Dec 03, 2021, https://www.euspa.europa.eu/european-space/eu-space-programme/what-gnss [Accessed 5/6/22].

[30] *EUSPA EO and GNSS Market Report*, EUSPA, European Union Agency for the Space Programme, Editor's Special Innovative Solutions for Health, ISSUE 1, Publications Office of the European Union, 2022. Available at: https://www.euspa.europa.eu/sites/default/files/uploads/euspa_market_report_2022.pdf.

[31] USGS, United States Geological Survey, "Historical perspective", Last updated: 08.07.12, https://pubs.usgs.gov/gip/dynamic/historical.html [Accessed 5/6/22].

[32] GPS Spotlight, "GPS and Tectonics", Last modified 2019-12-26, https://spotlight.unavco.org/how-gps-works/gps-and-tectonics/gps-and-tectonics.html [Accessed 5/6/22].

[33] M. Mittnacht, E. Gottzein, M. Hartrampf, A. Konrad, P.A. Krauss, C. Kühl, D. Marareskoul, A. Grechkoseev, and E. Islentjev, Commercial Use of GNSS Signals in GEO, *Elsevier IFAC Automatic Control in Aerospace*, 2004, pp.1097-1102.

[34] Sayak Kumer Pal, Archit Agrawal, V Manavala Ramanujam, Deepak Putrevu, Arundhati Misra, Ratna Ghosh, and Sanat K Biswas, Effect of Erroneous Observations in GPS-based LEO Satellite Orbit Determination, *Elsevier IFAC PapersOnLine*, 55-1, 2022, pp.204-210.

[35] HEXAGON, "What are Global Navigation Satellite Systems?", https://novatel.com/tech-talk/an-introduction-to-gnss/what-are-global-navigation-satellite-systems-gnss [Accessed 12/6/22].

[36] Jungang Yan, Lining Xing, Pei Wang, Leyuan Sun, and Yingwu Chen, A scheduling strategy to inter-satellite links assignment in GNSS, *Elsevier Advances in Space Research*, 67, 2021, pp.198-208.

[37] Ath. Zisopoulos, V. Mpalis, Chr. Liapakis, and A. Kolovos, *The Global Satellite Positioning System NAVSTAR/GPS*, Occasional Paper No. 4, HNCSA - Hellenic National Center for Space Applications, Hellenic Air Force General Staff, September 1992.

[38] NASA, "Global Positioning System History", Oct 27, 2012, Last Updated: Aug 7, 2017, https://www.nasa.gov/directorates/heo/scan/communications/policy/GPS_History.html [Accessed 12/6/22].

[39] HOW IT WORKS, "Bradford Parkinson: The father of GPS", By Ailsa Harvey, 26/11/2020, https://www.howitworksdaily.com/bradford-parkinson-the-father-of-gps/ [Accessed 12/6/22].

[40] GPS.GOV, "Selective Availability", Last modified on May 24, 2021, https://www.gps.gov/systems/gps/modernization/sa/ [Accessed 10/6/22].

[41] GPS.GOV, "GPS - Space Segment", Last modified on June 28, 2022, https://www.gps.gov/systems/gps/space/ [Accessed 10/7/22].

[42] GPS.GOV, "GPS - Control Segment", Last modified on August 9, 2021, https://www.gps.gov/systems/gps/control/ [Accessed 10/7/22].

[43] GPS.GOV, "The Global Positioning System", Last modified on February 22, 2021, https://www.gps.gov/systems/gps/ [Accessed 10/7/22].

[44] ESA Navipedia, "GPS Signal Plan", 2011, Last edited on 29 January 2021, https://gssc.esa.int/navipedia/index.php/GPS_Signal_Plan [Accessed 5/6/22].

[45] ESA Navipedia, "Time References in GNSS", 2011, Last edited on 4 November 2020, https://gssc.esa.int/navipedia/index.php/Time_References_in_GNSS [Accessed 10/7/22].

[46] GPS.GOV, "GPS Accuracy", Last modified on March 3, 2022, https://www.gps.gov/systems/gps/performance/accuracy/ [Accessed 10/7/22].

[47] GPS.GOV, "GPS Modernization", Last modified on November 3, 2017, https://www.gps.gov/systems/gps/modernization/ [Accessed 10/7/22].

[48] Islam Ashour, Mohamed El Tokhey, Yasser Mogahed, and Ahmed Ragheb, Performance of global navigation satellite systems (GNSS) in absence of GPS observations, *Ain Shams Engineering Journal*, 13, 2022, 101589, pp.1-7.

[49] SPACE NEWS, "Modern civilization would be lost without GPS", By Anusuya Datta, August 3, 2021, https://spacenews.com/modern-civilization-would-be-lost-without-gps/ [Accessed 1/6/22].

[50] Alexandros Kon. Kolovos, ed., *Persian Gulf War: A Critical Evaluation of The Role of Space Systems*, Occasional Paper No. 3, Hellenic National Center for Space Applications, February 1992.

[51] GPS.GOV, "GPS Applications", Last modified on November 25, 2014, https://www.gps.gov/applications/ [Accessed 10/7/22].

[52] Georgy M. Polischuk, and Sergey G. Revnivykh, Status and development of GLONASS, *Pergamon Acta Astronautica*, 54, 2004, pp.949-955.

[53] ESA Navipedia, "GLONASS Space Segment", 2011, Last edited on 22 June 2018, https://gssc.esa.int/navipedia/index.php/GLONASS_Space_Segment [Accessed 5/6/22].

[54] *Current and Planned Global and Regional Navigation Satellite Systems and Satellite-based Augmentations Systems*, United Nations, Office for Outer Space Affairs, International Committee on Global Navigation Satellite Systems Provider's Forum, United Nations, 2010. Available at: https://www.unoosa.org/pdf/publications/icg_ebook.pdf.

[55] ESA Navipedia, "GLONASS Ground Segment", 2011, Last edited on 18 September 2014, https://gssc.esa.int/navipedia/index.php/GLONASS_Ground_Segment [Accessed 5/6/22].

[56] ESA Navipedia, "GLONASS Architecture", 2011, Last edited on 22 June 2018, https://gssc.esa.int/navipedia/index.php/GLONASS_Architecture [Accessed 5/6/22].

[57] HEXAGON, "GLONASS", https://novatel.com/an-introduction-to-gnss/chapter-3-satellite-systems/glonass-global-navigation-satellite-system-russia [Accessed 5/6/22].

[58] ESA Navipedia, "GLONASS Signal Plan", 2011, Last edited on 30 October 2019, https://gssc.esa.int/navipedia/index.php/GLONASS_Signal_Plan [Accessed 5/6/22].

[59] GPS WORLD, "The System: GLONASS in April, What Went Wrong", By Gerhard Beutler, Rolf Dach, Urs Hugentobler, Oliver Montenbruck, Georg Weber, and Elmar Brockmann, June 24, 2014, https://www.gpsworld.com/the-system-glonass-in-april-what-went-wrong/ [Accessed 10/7/22].

[60] BeiDou Navigation Satellite System, "System", http://en.beidou.gov.cn/SYSTEMS/System/ [Accessed 15/6/22].

[61] VOA – China News, "China's Rival to GPS Navigation Carries Big Risks", John Xie, July 08, 2020, https://www.voanews.com/a/east-asia-pacific_voa-news-china_chinas-rival-gps-navigation-carries-big-risks/6192460.html [Accessed 15/6/22].

[62] Li Chengzhi, The Chinese GNSS – System development and policy analysis, *Elsevier Space Policy*, 29, 2013, pp.9-19.

[63] ESA Navipedia, "BeiDou Space Segment", 2011, Last edited on 18 September 2014, https://gssc.esa.int/navipedia/index.php/BeiDou_Space_Segment [Accessed 15/6/22].

[64] ESA Navipedia, "BeiDou Ground Segment", 2011, Last edited on 10 August 2018, https://gssc.esa.int/navipedia/index.php/BeiDou_Ground_Segment [Accessed 15/6/22].

[65] Alan Oxley, ed., *Uncertainties in GPS Positioning – A Mathematical Discourse, Chapter 6 – Signals From Satellites to Receiver – Other Satellite Navigation Systems*, Elsevier Ltd., 2017.

[66] THE ECONOMIC TIMES, "China celebrates completion of BeiDou Satellite System that could rival the US' GPS", Last Updated: July 31, 2020, https://economictimes.indiatimes.com/news/defence/china-celebrates-completion-of-beidou-navigation-satellite-system-that-could-rival-the-us-gps/articleshow/77283478.cms [Accessed 15/6/22].

[67] THE ECONOMIC TIMES, "Pakistan military to use Chinese navigation system BeiDou to improve interoperability", Last Updated: Aug 21, 2020, https://economictimes.indiatimes.com/news/defence/pakistan-military-to-use-chinese-navigation-system-beidou-to-improve-interoperability/articleshow/77675471.cms [Accessed 15/6/22].

[68] European Commission, Defence Industry and Space, "Galileo", https://defence-industry-space.ec.europa.eu/eu-space-policy/galileo_en [Accessed 15/6/22].

[69] eoPortal – Powered by ESA, Satellite Missions, "Galileo FOC", Nov 6, 2014, https://www-eoportal-org.translate.goog/satellite-missions/galileo-foc?_x_tr_sl=en&_x_tr_tl=el&_x_tr_hl=el&_x_tr_pto=op,sc [Accessed 15/6/22].

[70] *EU space programmes Galileo and Copernicus: services launched, but the uptake needs a further boost,* Special report, European Court of Auditors, 07, 2021. Available at: https://www.eca.europa.eu/lists/ecadocuments/sr21_07/sr_eus-space-assets_en.pdf.

[71] *Action Plan on synergies between civil, defence and space industries*, European Commission, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, COM(2021) 70 final, Brussels, 22.2.2021. Available at: https://ec.europa.eu/transparency/documents-register/detail?ref=COM(2021)70&lang=en.

[72] ESA Navipedia, "Galileo General Introduction", 2011, Last edited on 29 January 2021, https://gssc.esa.int/navipedia/index.php/Galileo_General_Introduction [Accessed 15/6/22].

[73] *Outcome of proceedings of the Council (Competitiveness) on 21-22 May 2007 - Resolution on the European Space Policy,* Council of the European Union, 10037/07, Brussels, 25 May 2007. Available at: https://data.consilium.europa.eu/doc/document/ST-10037-2007-INIT/en/pdf.

[74] EUSPA, European Union Agency for the Space Programme, "Galileo – System", https://www.gsc-europa.eu/galileo/system [Accessed 15/6/22].

[75] ESA Navipedia, "Galileo Space Segment", 2011, Last edited on 22 July 2021, https://gssc.esa.int/navipedia/index.php/Galileo_Space_Segment [Accessed 15/6/22].

[76] ESA, Applications, "Galileo constellation", 18/07/2014, https://www.esa.int/ESA_Multimedia/Images/2014/07/Galileo_constellation [Accessed 15/6/22].

[77] European Commission, Internal Market, Industry, Entrepreneurship and SMEs, "Galileo Incident of July 2019: Independent Inquiry Board provides final recommendations", Press Release, 19 November 2019, https://single-market-economy.ec.europa.eu/news/galileo-incident-july-2019-independent-inquiry-board-provides-final-recommendations-2019-11-19_en [Accessed 15/6/22].

[78] Resilient Navigation and Timing Foundation, "Galileo 6 Hour Outage 14 December – Updated Posted", Dec 19, 2020 https://rntfnd.org/2020/12/19/galileo-6-hour-outage-14-december-update-posted/ [Accessed 15/6/22].

[79] Walter F. Blanchard, Achieving GPS-Galileo interoperability: the challenges ahead, *Elsevier Space Policy*, 19, 2003, pp.95-99.

[80] UNITED NATIONS, Office for Outer Space Affairs, "International Committee on Global Navigation Satellite Systems (ICG)", https://www.unoosa.org/oosa/en/ourwork/icg/icg.html [Accessed 15/6/22].

[81] HEXAGON, "Satellite Based Augmentation Systems", https://novatel.com/an-introduction-to-gnss/chapter-5-resolving-errors/satellite-based-augmentation-systems [Accessed 15/6/22].

[82] Springer Open, "Status, perspectives and trends of satellite navigation", Published: 03 August 2020, https://satellite-navigation.springeropen.com/articles/10.1186/s43020-020-00023-x [Accessed 15/6/22].

[83] European Commission, Defence Industry and Space, "EGNOS", https://defence-industry-space.ec.europa.eu/eu-space-policy/egnos_en [Accessed 15/6/22].

[84] ESA Navipedia, "EGNOS Ground Segment", 2011, Last edited on 5 April 2019, https://gssc.esa.int/navipedia/index.php/EGNOS_Ground_Segment [Accessed 15/6/22].

[85] European Commission, Defence Industry and Space, "EGNOS Open Service", https://defence-industry-space.ec.europa.eu/eu-space-policy/egnos/egnos-open-service_en [Accessed 15/6/22].

[86] European Commission, Defence Industry and Space, “Safety-of-Life Service”, https://defence-industry-space.ec.europa.eu/eu-space-policy/egnos/safety-life-service_en [Accessed 15/6/22].

[87] European Commission, Defence Industry and Space, “EGNOS - Data Access Service”, https://defence-industry-space.ec.europa.eu/eu-space-policy/egnos/egnos-data-access-service_en [Accessed 15/6/22].

[88] ESSP, “Satellite navigation services prevail more influential than ever during the COVID crisis”, https://www.essp-sas.eu/communication/news/satellite-navigation-services-prevail-more-influential-ever-during-covid-crisis/ [Accessed 15/6/22].

[89] Daniel Schaad, EGNOS and WAAS – missing their potential in remote regions? The example of Greenland, *Elsevier Research in Transportation Business & Management*, 4, 2012, pp.29-36.

[90] GPS.GOV, “Augmentation Systems”, Last modified on February 10, 2022, https://www.gps.gov/systems/augmentations/ [Accessed 15/6/22].

[91] Indian Space Research Organisation, Department of Space, “Satellite Navigation Services”, https://www.isro.gov.in/SatelliteNavigationServices.html [Accessed 15/6/22].

[92] ESA Navipedia, “NAVIC”, 2011, Last edited on 22 April 2021, https://gssc.esa.int/navipedia/index.php/NAVIC [Accessed 15/6/22].

[93] Quasi-Zenith Satellite System (QZSS), “Overview of the Quasi-Zenith Satellite System (QZSS)”, https://qzss.go.jp/en/overview/services/sv01_what.html [Accessed 15/6/22].

[94] Quasi-Zenith Satellite System (QZSS), “Quasi-Zenith Satellite Orbit (QZO)”, https://qzss.go.jp/en/technical/technology/orbit.html [Accessed 15/6/22].

[95] Quasi-Zenith Satellite System (QZSS), “[Movie] Quasi-Zenith Satellite System “QZSS””, Nov. 01, 2018, https://qzss.go.jp/en/overview/downloads/movie_qzss.html [Accessed 15/6/22].

[96] Kolovos Alexandros Kolovos, ed., *Evaluating Turkish Space Policy: Outcome and Impact*, Institute of International, European and Defense Analyses, University of Macedonia, January 2018.

[97] Turkish Space Agency, “National Space Program – Regional Positioning and Timing”, https://tua.gov.tr/en/national-space-program [Accessed 15/6/22].

[98] KARI – Korea Aerospace Research Institute, “Satellite Navigation”, https://www.kari.re.kr/eng/sub03_08.do [Accessed 15/6/22].

[99] Grind GIS, “Application of GPS in Defence”, Amos Gikunda, July 2, 2020, https://grindgis.com/gps/application-of-gps-in-defence [Accessed 15/7/22].

[100] ESA Navipedia, “Military Applications”, 2011, Last edited on 18 September 2014, https://gssc.esa.int/navipedia/index.php/Military_Applications [Accessed 15/6/22].

[101] Bae Systems, “Defense Advanced GPS Receiver”, https://www.baesystems.com/en/product/defense-advanced-gps-receiver [Accessed 15/7/22].

[102] GPS.GOV, “Aviation”, Last modified on February 10, 2022, https://www.gps.gov/applications/aviation/ [Accessed 15/7/22].

[103] Faizana Naeem, Mujahid Mohsin, Usman Rauf, and Liaqat Ali Khan, Formal approach to thwart against drone discovery attacks: A taxonomy of novel 3D obfuscation mechanisms, *Elsevier Future Generation Computer Systems*, 115, 2021, pp.374-386.

[104] Thomas Dautermann, Civil air navigation using GNSS enhanced by wide area satellite based augmentation systems, *Elsevier Progress in Aerospace Sciences*, 67, 2014, pp.51-62.

[105] Ján Rostáš, and Filip Škultéty, Are today’s pilots ready for full use of GNSS technologies?, *Elsevier Transportation Research Procedia*, 28, 2017, pp.217-225.

[106] ESA Navipedia, “SBAS Fundamentals”, 2011, Last edited on 27 July 2018, https://gssc.esa.int/navipedia/index.php/SBAS_Fundamentals [Accessed 15/7/22].

[107] GPS.GOV, “Rail”, Last modified on November 17, 2021, https://www.gps.gov/applications/rail/ [Accessed 15/7/22].

[108] A. Di Fazio, D. Bettinelli, E. Louette, J.P. Mechin, M. Zazza, P. Vecchiarelli, and L. Domanico, European pathways to introduce EGNOS and Galileo for dangerous goods transport, *Elsevier Transportation Research Procedia*, 14, 2016, pp.1482-1491.

[109] GPS.GOV, “Public Safety & Disaster Relief”, Last modified on November 17, 2021, https://www.gps.gov/applications/safety/ [Accessed 15/7/22].

[110] ESA Navipedia, “Emergency Services”, 2011, Last edited on 16 September 2018, https://gssc.esa.int/navipedia/index.php/Emergency_Services [Accessed 15/7/22].

[111] EUSPA, European Union Agency for the Space Programme, European GNSS Service Centre, “GNSS Emergency Warning Service successfully tested”, https://www.gsc-europa.eu/news/gnss-emergency-warning-service-successfully-tested [Accessed 15/7/22].

[112] European Commission, Shaping Europe’s digital future, “112: EU Emergency number”, https://digital-strategy.ec.europa.eu/en/policies/112 [Accessed 15/7/22].

[113] EUSPA, European Union Agency for the Space Programme, European GNSS Service Centre, “The European 112-emergency number to reach new heights thanks to Galileo”, https://www.gsc-europa.eu/news/the-european-112-emergency-number-to-reach-new-heights-thanks-to-galileo [Accessed 15/7/22].

[114] Sharifah Mastura Syed Mohd Daud, Mohd Yusmiaidil Putera Mohd Yusof, Chong Chin Heo, Lay See Khoo, Mansharan Kaur Chainchel Singh, Mohd Shah Mahmood, and Hapizah Nawawi, Applications of drone in disaster management: A scoping review, *Elsevier Science & Justice*, 62, 2022, pp.30-42.

[115] Jian Li, Gongliu Yang, Qingzhong Cai, Haofei Niu, and Jing Li, Cooperative navigation for UAVs in GNSS-denied area based on optimized belief propagation, *Elsevier Measurement*, 192, 2022, 110797, pp.1-10.

[116] BBC NEWS, “Combat drones: We are in a new era of warfare – here’s why”, 4 February 2022, https://www.bbc.com/news/world-60047328 [Accessed 22/7/22].

[117] *Civil and military drones - Navigating a disruptive and dynamic technological ecosystem*, European Parliament, Briefing, European Union, 2019. Available at: https://www.europarl.europa.eu/RegData/etudes/BRIE/2019/642230/EPRS_BRI(2019)642230_EN.pdf.

[118] IdeaForge, “Border Security”, https://www.ideaforge.co.in/drone-uses/border-security-applications/ [Accessed 22/7/22].

[119] IdeaForge, “Disaster Management”, https://www.ideaforge.co.in/drone-uses/disaster-management/ [Accessed 22/7/22].

[120] Healthcare Packaging, “Montreal is Testing Drones as Medical Delivery Vehicles”, By Tim Hayes, https://www.healthcarepackaging.com/markets/medical-devices/-packaginig/news/13702056/montreal-is-testing-drones-as-medical-delivery-vehicles [Accessed 22/7/22].

[121] George P. Petropoulos, and Prashant K. Srivastava, *GPS and GNSS Technology in Geosciences, Chapter 3 – Security of GNSS*, Elsevier Inc., 2021.

[122] GOGEOMATICS CANADA, “GNSS Jamming vs. Spoofing”, Written by: Jordan Palk, April 12, 2022, https://gogeomatics.ca/gnss-jamming-vs-spoofing/ [Accessed 22/7/22].

[123] Omid Sharifi-Tehrani, Mohamad F. Sabahi, and M.R. Danaee, GNSS jamming detection of UAV ground control station using random matrix theory, *Science Direct The Korean Institute of Communications and Information Sciences ICT Express*, 7, 2021, pp.239-243.

[124] Ali Jafarnia-Jahromi, Ali Broumandan, John Nielsen, and Gérard Lachapelle, GPS Vulnerability to Spoofing Threats and a Review of Antispoofing Techniques, *Hindawi Publishing Corporation International Journal of Navigation and Observation*, Volume 2012, Article ID 127072, pp.1-16.

[125] Daniele Borio, and Pau Closas, A Fresh Look at GNSS Anti-Jamming, *Inside GNSS - GNSS Anti-Jamming*, September / October 2017, p.54-61.

[126] *GNSS User Technology Report*, European Global Navigation Satellite Systems Agency, Editor’s Special on Space Data for Europe, Issue 3, Publications Office of the European Union, 2020. Available at: https://www.euspa.europa.eu/sites/default/files/uploads/technology_report_2020.pdf.

[127] GPS WORLD, “Demand rises for defense solutions in NAVWAR and GPS-denied environments”, November 21, 2019, https://www.gpsworld.com/demand-rises-for-defense-solutions-in-navwar-and-gps-denied-environments/ [Accessed 22/7/22].

[128] *Above Us Only Stars - Exposing GPS Spoofing in Russia and Syria*, C4ADS innovation for peace, 2019. Available at: https://static1.squarespace.com/static/566ef8b4d8af107232d5358a/t/5c99488beb39314c45e782da/1553549492554/Above+Us+Only+Stars.pdf.

[129] nextBig Future, “Russia will place GPS jammers on 250,000 cellphone towers to reduce enemy cruise missile and drone accuracy in the event of large scale conventional war”, By Brian Wang, October 18, 2016, https://www.nextbigfuture.com/2016/10/russia-will-place-gps-jammers-on-250000.html#more-1189 [Accessed 22/7/22].

[130] Alexandros K. Kolovos, ed., *Intelligence and Cyberattacks in the Russo-Ukrainian Conflict: The Role of Space*, Working Paper Series No. 4, Laboratory of Intelligence & Cyber-Security, University of Piraeus, July 2022.

[131] The Maritime Executive, “Mass GPS Spoofing Attack in Black Sea?”, By Dana Goward, Published Jul 11, 2017, https://maritime-executive.com/editorials/mass-gps-spoofing-attack-in-black-sea [Accessed 22/7/22].

[132] NATO – North Atlantic Treaty Organization, Allied Maritime Command, “Electronic Interference in Mediterranean”, Dec 12 2019, https://shipping.nato.int/nsc/operations/news/2019/electronic-interference-in-mediterranean [Accessed 22/7/22].

[133] Geospatial World, “Why PNT is vital for national security?”, by Nibedita Mohanta, https://www.geospatialworld.net/prime/why-pnt-is-vital-for-national-security/ [Accessed 22/7/22].

[134] NATO – North Atlantic Treaty Organization, Allied Maritime Command, “GNSS Electronic Interference in the Mediterranean”, https://shipping.nato.int/nsc/operations/news/2021/gnss-electronic-interference-in-the-mediterranean [Accessed 22/7/22].

[135] SPACE.com, “Russia is jamming GPS satellite signals in Ukraine, US Space Force says”, by Elizabeth Howell, April 12, 2022, https://www.space.com/russia-jamming-gps-signals-ukraine [Accessed 22/7/22].

[136] EASA – European Union Aviation Safety Agency, “EASA publishes SIB to warn of intermittent GNSS outages near Ukraine conflict areas”, 17 Mar 2022, https://www.easa.europa.eu/en/newsroom-and-events/news/easa-publishes-sib-warn-intermittent-gnss-outages-near-ukraine-conflict [Accessed 22/7/22].