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# OVERVIEW OF GNSS SYSTEMS AND THEIR OPERATION

# PREGLED GNSS SISTEMOV IN NJIHOVO DELOVANJE

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## Abstract

In this paper, we present the beginnings of navigation and what it was that drove its development forward. We will also present the development of global navigation satellite systems, known as GNSS, as well as all the most important GNSS systems and their development. Finally, the basic operation of such systems and the differences between them will be presented.

## Povzetek

V nalogi bomo predstavili začetke navigacije in kaj je poganjalo njen zgodovinski razvoj. Ogledali si bomo tudi razvoj globalnih navigacijskih satelitskih sistemov, ki jih poznamo pod kratico GNSS, se podrobneje poglobili v razvoj najpomembnejših med njimi in obravnavali njihovo osnovno delovanje ter razlike med njimi.

## 1 INTRODUCTION

Amongst the more important questions that humanity has asked itself throughout history is undeniably 'Where am I?' We could also add to this question, 'where is someone else?' or 'where is an object?' These questions seem very simple at first, but humanity has been looking for a solution for a long time. The solution came with the introduction of global navigation satellite

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systems or GNSS for short. We use navigation systems every day. Often, we are not even aware of this, nor how much they make our daily tasks easier. Almost every smart device and every vehicle is already equipped with a GNSS signal receiver. Devices that show us the route and guide us to our destination have replaced traveling with a map in hand. We can see our location at any time, as well as how much longer it will take to reach our destination.

## 2 HISTORY

Man has always wanted to travel from point A to point B as fast and as safely as possible, orientating himself with the help of objects in nature. This; however, was much harder at sea. The Phoenicians navigated using the sun and the stars in 2000 BC. The distance travelled and the estimated speed of movement was measured using an hourglass. Even the Egyptians in 1500 BC relied on the sun and the stars. They also navigated using a simple depth gauge and wind as Vikings did between 900 and 1000 AD. It is clear that navigation began to develop at sea. Amongst the most important discoveries for navigation, especially by sea, was the compass. A lead cord at the end was also practical, used to sample the bottom and measure depth. The oldest known navigation system was used by the Greeks, who used a system of lighting bonfires on the tops of hills to sail across the Mediterranean Sea. These bonfires served as a point of reference for sailing at night. They started making and using maps with merely directions and ports. The problem was that they did not have a method that allowed the spherical surface of the Earth to be displayed. In around 1500, sailors began using devices to measure the angle of the sun and stars above the horizon, which they then used to determine latitude. Figure 1 shows a sextant precursor that was less accurate. Using the device, they measured the angle between the horizon and the sun or stars. [1]

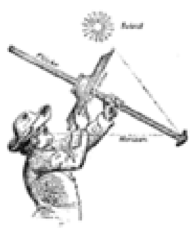

***Figure 1:*** *The predecessor of the sextant [1]*

Methods of measuring time were still very inaccurate. Even the best devices were losing about 10 minutes a day, which meant a huge loss over several weeks of sailing, and consequently an inaccurate location. Even speed measuring was improving very slowly. They were using the knot as a unit for measuring speed on water. It was not until the 18th century, when cartography developed and it was thus possible to represent the earth in a spherical shape, that the compass came into play, allowing the determination of cardinal direction by accurately measuring time so that longitude could then be identified. In 1884, an agreement was signed confirming the Greenwich meridian as the Prime meridian. After the introduction of the universal radio signal from Greenwich, all that was needed was an ordinary clock and a radio on board to be able to calculate the exact location. In 1935, the British physicist Robert Watson developed the first useful radar system that was able to determine the location of objects outside the field of view using radio waves. Between 1940 and 1943, a navigation system called Loran was developed in the United States. It had limited signal coverage. [1]

# 3 DEVELOPMENT OF GNSS

There are currently four main types of GNSS systems in the world: the American GPS, the Russian GLONASS, the European Galileo and the Chinese BeiDou. In addition to the listed major GNSS, there are also regional navigation satellite systems known as RNSS. They complement GNSS by providing information on the accuracy, integrity and accessibility of the results provided by the GNSS system.

## 3.1 Development of GPS

The development of GPS was encouraged by the launch of the Russian satellite Sputnik into orbit on October 4, 1957. Based on a signal emitted by Sputnik, a team of American experts began their research. They theorised that the Doppler shift could be used to determine the exact location of a satellite. They then turned this idea upside down and put forward a new theory. If you know the location of the satellite, then you can determine the location of the navigator anywhere on Earth. Based on this, the US Navy developed a system for locating submarines. In 1964, solar cells powered the Transit satellite. To determine location, the submarine had to expose the antenna to the surface within 10 to 16 minutes. The resulting location could then be provided with an accuracy of 25 metres in two dimensions. The deviation was much greater if the object was moving. Transit laid the foundations on which they later built the GPS system as we know it today. The US Air Force also conducted its satellite navigation programme in a three-dimensional space called the 621B. They focused their research on signal modulation, user data processing, receiver accuracy, error analysis, system costs, and Earth orbit. The greatest progress has been made in signal research. They also found the most effective signal, which they termed CDMA. The CDMA signal was scattered over a wide range of radio frequencies. With it, they achieved an accuracy of 5 metres in three-dimensional space. [2]

With the merger of the Transit and 621B projects, a new project called NAVSTAR–GPS was created in 1973. The most important engineering challenges involved defining the specifics of the CDMA signal structure, developing space-based atomic clocks, achieving fast and accurate satellite orbit predictions, ensuring longer life of spacecraft, and developing custom GPS equipment. [3]

In 1978, the first NAVSTAR BLOCK I development satellite was launched into orbit, followed by ten more across the years leading up to 1985. The system was designed for military purposes, which changed in 1983 when a Soviet fighter jet shot down a civilian passenger plane that accidentally found itself in Soviet airspace. Following this event, US President Ronald W. Reagan announced that the NAVSTAR–GPS system would also be available for civilian use after it was fully operational. The initial operational capacity (IOC) was reached on 8 December 1993. BOCK I was replaced by nine BLOCK II satellites and 15 BLOCK IIA satellites. The system was declared fully operational (FOC) on 25 April 1995. An additional four BLOCK IIA satellites and 13 new BLOCK IIR satellites were later launched. [4], [5]

## 3.2 Development of GLONASS

Development of GLONASS began in 1976, with the first satellite being launched into orbit in 1982. It formed part of the prototype generation Block I. The others were launched by 1985. The first generation was launched by 1990 and operated for four and a half years. Until the full establishment of the system, which required 24 operational satellites, the Russians had to launch 70 satellites. Many satellites were lost due to failed launches and many orbit failures. The system was declared FOC in 1996. The collapse of the Soviet Union greatly affected GLONASS. The system did not receive any investments and began to break down. This occurred to such an extent that by 2002, only seven satellites remained. It then began to slowly recover. The second-generation satellite has remained in orbit since 2003, with an increased lifespan of up to seven years and an improved level of atomic clock stability. By 2011, the GLONASS system had reached FOC again. The second generation of satellites are equipped with an additional L2OF signal, which is intended for civilian use and allows the elimination of the ionosphere delay. [6]

## 3.3 Development of Galileo

Galileo is a European GNSS that was not built for military purposes and is run by civil society. Europe wanted to offer an alternative to the American and Russian GNSS. They collaborated with the European Space Agency (ESA) on its development. Development began in 1999, when Germany, France, Italy and England merged, each with its own concept. A team of experts from all four countries then drew up a first phase plan, which was confirmed by the EU and ESA in 2003. [7]

Galileo encountered financial problems because of issues with the US, which opposed the establishment of the system and put pressure on the European Union to stop the project. Europe identified its need for its GNSS and reached an agreement with the US concerning the security issues. The test satellite was launched in 2005. Due to financial difficulties, the project was taken over by the EU in 2007, while in the following year a second test satellite called GIOVE-B was launched into orbit, which together with the first GIOVE-A formed part of the first IOV phase. Based on the results, four IOV satellites were then launched in 2011 and 2012 for ground and space control segment testing purposes. In the second phase of the IOC, two satellites were launched into orbit in 2014, but they were used only for scientific purposes. By the end of 2016, the Galileo system was once again able to transmit a signal that could be used to determine location and time. There were 18 satellites in orbit, of which only 12 were operational. The Galileo system had 26 satellites in 2019, of which 22 were in operation. [6]

## 3.4 Development of BeiDou

Eager for greater independence in order to increase its economic and social development, the Chinese government decided to establish its own GNSS. Development began in 1983 with the idea of two geostationary satellites, which were successfully tested in 1989, marking the beginning of a system called BeiDou. Experimental BDS-1 systems began to be developed in 1994. Two geostationary satellites were launched in 2000, while another was later launched in 2003. The system made it possible to locate and communicate via short messages in the area of China. The second phase of BDS-2 began in 2004. The system consisted of 14 satellites located at different altitudes in orbit that emitted signals at three different frequencies. The system allowed Asia and Pacific residents to determine location, navigation and exact time. The regional system was declared FOC on 27/12/2012 and was free of charge. The third phase of BDS-3 began in 2015 with five new satellites designed to perform tests of new signals. Exactly six years after the proclamation of the FOC, the system became global with 18 satellites in mid-Earth orbit and one in geostationary orbit. [6]

# 4 GNSS BASIC OPERATION

In order to determine the position of an object, GNSS uses the technique of accurately measuring the time required by the signal from the transmitter to the receiver. It is important that the transmitter is in a known location. The travel time of the signal is then multiplied by its speed. The result given is the distance from the transmitter to the receiver. This positioning technique is called geometric trilateration. The more accurate transmitter locations we have, the more accurate the receiver location will be.

## 4.1 Determining the position of the satellite

The movement of satellites can be both predicted and accurately determined. The motion of satellites is influenced by the gravity of the Earth, which is not completely round and does not have the same density. The forces of the Sun and Moon and other celestial bodies also influence the path of satellites. Satellites do not travel in a perfect vacuum and are subject to inhibitory force. The force of the sun's radiation and the reflection of photons from the Earth also affects satellites. This occurs to such an extent that when moving towards the Sun, the satellites slow down and when moving away from the Sun, they accelerate. For this reason, ground base stations are used, with the help of which we are able to calculate the location of the satellite within 1 metre. Location data is divided into almanacs and ephemeris data. The almanac contains data on the path of satellites over a long period of time. Each satellite has an almanac for all other satellites in the constellation. The ephemeris data contain the exact location of the satellite for a short time in the future. Each satellite submits the location to itself, while the receiver must obtain information from each satellite in the field of view separately. With the location information, the receiver also obtains information about its validity. Receivers store data on ephemeris and almanacs in internal memory. Satellites have very accurate atomic clocks and simultaneously transmit a signal, while the signal path defines the distance of the satellite from the receiver. With the help of a satellite signal, the receiver can determine the time. Determining the time is more accurate if there are multiple satellites. [7]

## 4.2 Two-dimensional location determination

The measured distance of the satellite from the receiver is used for further calculation of the location. In the case of a single transmitter, such a result would mean that the receiver is located somewhere on the circle, distant for the result obtained. This is shown in Figure 2 a). If you want a more accurate result, you could use two transmitters with a known location. Hypothetically, we would determine the two points where the receiver is located. These two points define the intersections of the circles, as shown in Figure 2 b) as A and B. With the added third transmitter, our result is reduced to one point. This is the intersection of all three circles, as shown in Figure 2 c). It is important that all of the transmitters and the receiver have a precisely synchronised clock with each other.

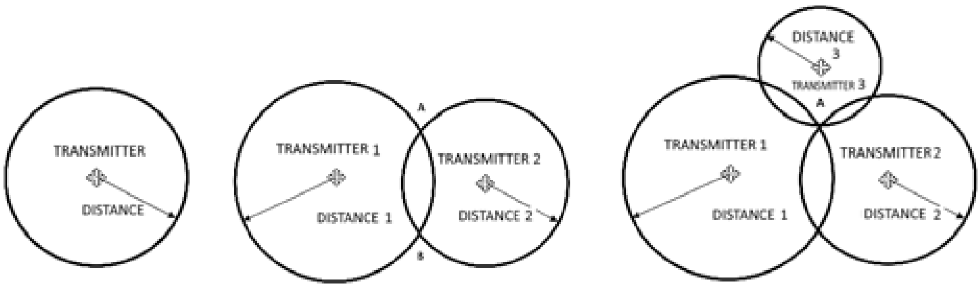


***Figure 2:*** *2D distance determination with a) one, b) two or c) three transmitters*

## 4.2 Three-dimensional location determination

Let us start with one satellite with a known location and a receiver at an unknown location. Figure 3 a) shows that the measurement result is a sphere around the satellite, while the location of the receiver is on the surface of this sphere. If we add a second satellite that emits a signal at the same time as the first, we see an additional sphere that is concentric to the second satellite. The receiver is also located on the surface of second sphere. Since the receiver must be located on the surface of both spheres at the same time, it may be on the perimeter of the shaded circle shown by the arrow in Figure 3 b). It could also be at a point that touches both spheres, but this would only happen if the receiver was co-linear with the satellites. When the third satellite is added, the surface of its sphere intersects the shaded plane of Figure 3 b) at two points, as shown in Figure 3 c). Only one is right. Note that the points are mirrored with respect to the plane of the satellites. For a receiver on the ground, it makes sense that the right location is the one that is closer to the ground. [8]

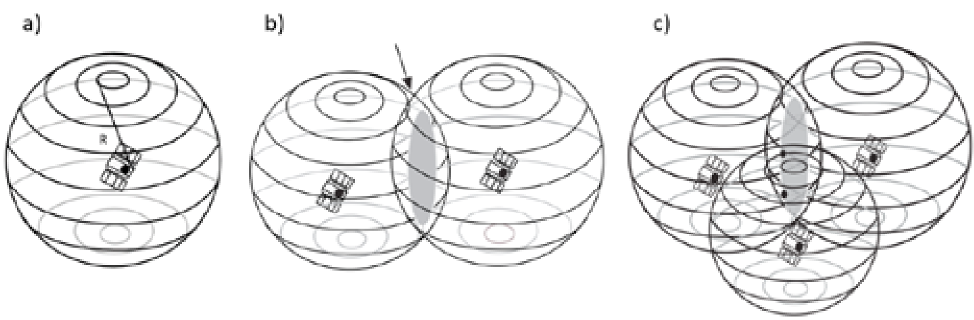


***Figure 3:*** *3D distance determination with a) one, b) two or c) three transmitters [8]*

For the mathematical calculation of the positions of transmitters and receivers, it is necessary to choose a reference coordinate system. For the purpose of determining the position of satellites in orbit, it is convenient to use the Earth's concentric inertial coordinate system ECI, where the starting point is at the centre of the Earth. The axes are fixed and directed in the direction of the stars, taking into account Newton's laws of motion and gravity. It is necessary to determine the position of the earth at a given time. The ECI GPS coordinate system uses the orientation of the equatorial plane on 1.1.2000 at 12.00 and is known as the J2000 system. [8]

## 4.3 Measurement errors

Even a small error in just one of the measurements can result in a difference of tens of metres. The most common sources of errors are atmospheric disturbances in the troposphere and ionosphere. Disturbances are reflected in a decrease in the speed of light and have less impact at night. Precise atomic clocks in satellites, calibrated to 3 nanoseconds accurate, are very important. Other errors include electrical noise in the signal, signal path error as it can bounce off objects and prolong the path, incorrect satellite location, and satellite placement. The impact of errors can be reduced by increasing the number of satellites.

# 5 GPS

GPS consists of a space, control and user segment. The space segment consists of 24 operational satellites arranged in six orbital planes, which are offset from each other by 60 ° and together form a complete 360 °. In addition to operational satellites, there are three backup satellites. All are located in the middle Earth orbit at an altitude of about 20,200 km above the earth's surface. The satellites orbit the earth at an angle of 55 ° and an orbital time of 11 hours and 56 minutes. The radius of the satellites is 26,560 km. The satellites are positioned so that the receiver has a connection to at least four satellites anywhere on Earth at any time. The main task of the control segment is to monitor satellites and determine and predict their exact location, as well as to take care of the integrity of the system, the atomic clocks, atmosphere and satellite almanacs. The data collected by the control segments is then uploaded to the satellites. The control segment consists of 16 optimally positioned earth stations around the world that send data to satellites via 11 earth antennas. The main control station is located at the Schriever Air Force Base in Colorado. The frequencies for sending the PRN signal are L1 (1575.42 MHz) and L2 (1227.60 MHz). The publicly available C/A code for civil use is implemented in the L1 signal, while the more precise P(Y) code, which is protected, is implemented in both frequencies. It uses WGS 84 for the GPS reference coordinate system. The user segment is usually called a GPS receiver, which processes signals sent from satellites to determine position, speed and time. A GPS receiver basically consists of an antenna, a receiver, a processor, a screen, and a power supply. It can be mounted on vehicles, ships or aircrafts, providing a precise position regardless of weather conditions. [6], [9]

## 5.1 GPS modernisation

Later, L2C, L5 and L1C signals for civilian purposes were developed. The L2C has been available since 2005, when it was sent into orbit by Block IIR-M satellites. Due to the increased signal strength, it is more accessible in urban centres, cities with increased vegetation, and indoors. The simultaneous use of L2C and L1 C/A signals allows users to coordinate ionosphere shift. The L1C signal was developed with the Galileo system. The signal provides better reception in urban environments and has greater resistance to the reflection effect. For military purposes, the M code was developed. The L3 signal is reserved for the transmission of data from satellites to Earth stations and is used to detect nuclear explosions in the Earth's atmosphere or near space. The L4 signal is used for additional research in the ionosphere. The L5 signal has been added to the system upgrade and is intended for a security system called Safety of Life. The signal is stronger than L2C and allows better reception, greater breakthrough and resistance. In combination with the L1 C/A and L2C signals, as well as the three-frequency technique, it enables more precise location determination up to 1 metre without the use of additional systems. [6]

The GPS system satellite constellation consists of old and new. There is currently no longer a Block IIA generation satellite. There are 7 active Block IIR satellites, seven BLOCK IIR-M satellites, 12 Block IIF satellites and 4 GPS III / IIIF satellites. As of February 2, 2022, 30 satellites in the GPS constellation are operational. [10]

# 6 GLONASS

The space segment of the GLONASS system on 1 March 2022 consists of 25 satellites, of which 22 are operational. Two satellites are in the maintenance phase and one is in the test flight phase. The satellites are arranged in three MEOs with a spacing of 120 °. The satellites are spaced 45 ° apart in the orbital plane. They are located at an altitude of 19,100 km above the Earth's surface. Each satellite needs 11 hours, 15 minutes and 44 seconds to make its way around the Earth. The layout allows constant coverage on the ground and altitudes up to 200 km. The constellation can be expanded to 64 satellites. Each satellite in the GLONASS constellation transmits the same PRN code, but at a different frequency. Unlike others, the GLONASS system uses the technique of differentiating FDMA signals and not CDMA. FDMA technology means multiple access with frequency distribution, while in CDMA technology satellites alternately send signals on one frequency without mixing the signals with each other. Signals are transmitted in two bands. L1 has a midrange of 1602 MHz and delays of 0.5625 MHz and L2 1246 MHz and delays of 0.4375 MHz. A constellation with 24 satellites needs 14 channels, which means that two of satellites located on opposite sides of the globe use the same channel. [6], [8]

## 6.1 GLONASS modernisation

GLONASS satellites are known as Uragan. To this day, six satellite models have been launched, including a prototype and a zero-generation, belonging to Block I. Satellites of this generation were launched into orbit between 1982 and 1985 and had a lifetime of one year. The first generation included the Block IIa, Block IIb and Block IIv satellite models, which had their lifetime increased to four and a half years. They were launched between 1985 and 1990. The second generation of GLONASS-M satellites were into orbit from 2003 onwards. Their lifetime was extended to seven years. They also had improved atomic clock stability and were able to emit a second civil L2OF signal with the ability to eliminate ionosphere delay. The last satellite in the current constellation GLONASS was launched into orbit on October 25 2020 and is still in the test phase. Prior to this, two more satellites were launched in the same year, which are currently fully operational. They are all GLONASS-K generations, which will eventually be replaced by the GLONASS-K2 generation. Although this should have started as early as 2020, to this day no satellite of this generation has been launched and they are still in development. At the same time, there is a plan to launch six GLONASS-B generation satellites into HEO in order to increase accuracy in urban centres, while GLONASS-KM satellites are also being developed for additional civilian signals. The ground control segment is also in the modernisation phase. The main control centre of the ground control segment is located in Krasnoznamensk, near Moscow. The biggest problem is that almost all control stations were built on the territory of the former Soviet Republic, which means that satellites cannot be tracked and updated at all times. To solve this problem, two control stations were built, one in Brazil in 2014 and one in South Africa in 2017, which increased the accuracy of satellite locations in orbit, the accuracy of satellite atomic clocks, and improved signal coverage of the Earth. The construction of a station in India is also planned. Due to the use of FDMA signal, the manufacture of receivers was more complex and expensive. With the transition to CDMA signal, production is cheaper and more affordable. The ephemeris of the GLONASS system is given according to the ground reference coordinate system PZ-90. Its latest version PZ-90.11 was approved in 2014, is ITRF2014 compliant at the centimetre level, and allows better compatibility with other GNSS. [6]

# 7 GALILEO

The Galileo system is not yet at full operational capacity. When the system is complete, the satellites will be divided into three orbital planes inclined at an angle of 56 ° to the equator. There will be one backup satellite in each plane in case of an operational failure. The satellite will take 14 hours to travel around the Earth. Galileo will be fully compatible with the American GPS system, which will further improve the accuracy of the system. Six to eight satellites are expected to be visible from most locations on Earth at any given time, which means an accuracy of a few centimetres. The satellites are located at an altitude of 23,222 km. There are currently 22 fully operational satellites and 4 test satellites in the constellation with a lifetime over 12 years. Full operational capacity is expected in 2023. [11]

The ground segment consists of control and user. Control segment stations are set up around the world and allow you to obtain accurate information related to location, navigation and time. However, the majority of stations are within the European territory. The user segment has different types of receivers. They are used for navigation in cars, mobile devices and other devices that require accurate location. [6]

Galileo satellites emit 10 different navigation signals in the frequency bands E1, E5a, E5b, E6. At the same time, the satellites emit a SAR signal in the band intended for rescue services between 1544 MHz and 1545 MHz. The frequency ranges of Galileo signals are similar to the frequency ranges of the GPS system, so special modulation is required to avoid signal overlap. Galileo signals provide a variety of services for both civilian and military use. Amongst the most famous is the Open Service, which is free for use primarily in vehicles and smart devices. It can be used by anyone who has a Galileo receiver anywhere in the world and allows for the accurate determination of location. The system has up to 4-metre horizontal accuracy and up to 8-metre vertical accuracy when using two frequency receivers. This accuracy is slightly worse when using a single frequency receiver. High Accuracy Service is a paid closed service. The signal has improved accuracy and features simultaneous access to the signal on multiple frequencies. The Public Regulated Service is intended for government use. Police, firefighters and similar services can use it. It is transmitted at two different frequencies to make the signal more resistant to intentional interference. The signal is intended for use in crisis situations. The SAR signal is designed to search for and rescue victims, allowing you to search around the world within 10 minutes and to be accurate to 5 km. A feedback signal is also introduced to inform the victim that their signal has been received and located. [6]

# 8 BEIDOU

The BeiDou navigation system is also known by the acronym BDS. Satellites placed in three different orbits represent the space segment. The satellites are located in GEO, IGSO and MEO orbits. Compared to other systems, BDS has the advantage that it has more satellites in higher orbits and better results in lower lying parts of the Earth. The earth segment consists of several earth stations run by the main control station. The clock is synchronised and data is uploaded onto the satellites by a special station, in addition to which there is an observation station, as well as management and control stations, that take care of the connection to the satellites. The BDS user segment offers a variety of products, systems and services that may be compatible with other GNSS. [12]

The BDS system has a total of 35 satellites, 27 of which are intended for operational tasks and 3 of which will be spare. Like other systems, it is always fully operational 24 satellites. They will be divided into three orbital planes in the MEO with a delay of 120 °. The satellites will be at an altitude of 21,528 km and an inclination of 55 °. Satellites take 12 hours and 35 minutes to travel around the Earth. Five satellites will be located in GEO at an altitude of 35,786 km and the other three in IGSO with a delay of 120 °. The GEO and IGSO satellites are designed to cover China and the periphery of Asia, while the MEO satellites are designed to cover the rest of the Earth. [6]

On 31 July 2020, the Chinese government declared the system fully operational, joining the US's GPS, Russia's GLONASS and Europe's Galileo. The BeiDou-3 project was completed, with the system beginning to be used by more than 100 countries, mostly in Asia. With the new generation of BeiDou-3, China has started broadcasting a new civilian B1C signal at 1575.420 MHz, just like the L1 signal at GPS and the E1 signal at Galileo. This required modulation. Since open signals B2a and B2b are transmitted at the same frequencies as Galileo signals E5a and E5b, the possibility of joint processing is open. The system enables both open and closed services, with the open system being for civilian use and free of charge. It provides accuracy of up to 5 metres in the Asia-Pacific region and up to 10 metres globally. A closed system for authorised users allows for more secure and accurate location, speed, time and communication. The control segment on Earth is limited, as all of its stations are located in China. The system uses its reference coordinate system called CGCS2000. [12]

# 9 CONCLUSION

In this article, we have presented the global navigation satellite systems that are currently operational. The GPS system is still by far the most important and most developed, as well as the most widely used. Despite the fact that all but the Galileo system were initially built for military purposes, their use in civilian work has become so widespread that no one thinks of them as part of the military infrastructure anymore. In addition to GNSS, there are also smaller so-called regional systems that serve to obtain more accurate data in a certain area. Satellites of such systems are placed only in geostationary orbit. Typical representatives of such systems include the Indian IRNSS and the Japanese QZSS.

GNSS systems have become so common that we can hardly imagine life without them. Wherever we go, they accompany us and make our lives easier. We often forget their basic purpose, which is something we should fear. In wartime as well as in peacetime, such systems represent an excellent tool for espionage, monitoring the adversary's military capabilities, as well as for coordinated attacks. We definitely want GNSS to be primarily used for civil and defence purposes.

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