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EXCLUSIVE STUDY ON SATELLITE COMMUNICATION AND -AVIGATION SYSTEND FUTURE OF GNSS IN 21ST CENTURY

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Abstract: Since ancient times, people have looked at the sky to navigate. Long time ago, sailors relied on the patterns of stars in the night sky to determine their location and their desired destination. Nowadays, all we require is a simple handheld Global Positioning System (GPS) receiver to pinpoint our precise location anywhere on Earth. Nevertheless, we still depend on objects high in the sky to ascertain our whereabouts and routes. In the contemporary era, instead of stars, we utilize satellites. There are over 30 navigation satellites zooming around high above our planet which can precisely pinpoint our location. Global Navigation Satellite Systems (GNSS) comprise constellations of satellites orbiting Earth, which broadcast their positions in space and time, along with networks of ground control stations and receivers that calculate ground positions through trilateration. GNSS technology is utilized in various forms of transportation, including space stations, aviation, maritime, rail, road, and mass transit. Positioning, navigation, and timing (PNT) play a pivotal role in telecommunications, land surveying, law enforcement, emergency response, precision agriculture, mining, finance, scientific research, and more. They are used for managing computer networks, air traffic, power grids, and numerous other systems. This is an analytical study aimed at depicting the satellite and communication system, encompassing its operational principles, history, categories, and applications.

Key words: GNSS, GPS, GLONASS, Galileo, BeiDou, QZSS, GAGAN, DGPS

Introduction

Currently, GNSS comprises four fully operational global systems: the United States' GPS, Russia's Global Navigation Satellite System (GLONASS), Europe's European Satellite Navigation System (GALILEO), and China's COMPASS or Bei-Dou. Simultaneously, two well-known regional satellite navigation systems have emerged: India's Regional Navigation Satellite System (IRNSS) and Japan's Quasi-Zenith Satellite System (QZSS). Now, nearly all of these global and regional systems are fully operational, providing the users access to positioning, navigation, and timing signals from more than 100 satellites.[1] Furthermore, there are satellite-based augmentation systems, such as the US' Wide-area Augmentation System (WAAS), the European Geostationary Navigation Overlay Service (EGNOS), the Russian System of Differential Correction and Monitoring (SDCM), the Indian GPS Aided Geo Augmented Navigation (GAGAN), and the Japanese Multi-functional Transport Satellite (MTSAT) Satellite-based Augmentation Systems (MSAS). Combining these systems with proven terrestrial technologies like inertial navigation will open up new possibilities for socio-economic benefits, both on an institutional and personal level. These applications demand not only accuracy but, most importantly, reliability and integrity. Safety-critical transportation applications, such as civilian aircraft landings, have strict accuracy and integrity requirements. Once again, the successful completion of the work carried out by the International Committee on Global Navigation Systems (ICG), particularly in establishing interoperability among the global systems, will enable GNSS users to use a single device to receive signals from multiple satellite systems. This will provide additional data, especially in urban and mountainous areas, and enhance the accuracy of timing and position measurements. To reap the benefits of these advancements, GNSS users must stay updated on the latest developments in GNSS-related fields and develop the capability to utilize multi-GNSS signals.[2]

Hence, the specific goals of carrying out the GNSS priority area of the United Nations Program on Space Applications involve demonstrating and comprehending GNSS signals, codes, biases, practical uses, and potential modernization effects. In 2005, the endeavors of the Action Team on GNSS, composed of 38 countries and 15 intergovernmental and non-governmental organizations, led to the formation of the International Committee on Global Navigation Satellite Systems (ICG), operating under the United Nations' umbrella.[3] The ICG aims to foster and facilitate the harmony, compatibility, and openness among all satellite navigation systems, endorsing and safeguarding the use of their accessible service applications for the benefit of the global community. ICG's vision is to ensure the best satellite-based positioning, navigation, and timing services for peaceful purposes, accessible to everyone, everywhere, at any time. The establishment of ICG highlighted that GNSS had become a genuinely international asset and underscored the commitment of providers and users of positioning, navigation, and timing services to sustain GNSS services for the welfare of all humanity in the future.[4] Starting from 2006, a sequence of regional workshops has concentrated on employing GNSS for air, sea, land,

and personal navigation, Location-Based Services (LBS), Intelligent Transport Systems (ITS), and Search and Rescue (SAR) operations, as well as investigating the impact of space weather on the precise positioning uses of GNSS. The overarching aim of these workshops is to outline the demands and prerequisites of GNSS end-users while establishing a framework for scientific research empowered by GNSS.

GPS is a system composed of three main parts: satellites, ground stations, and receivers. Satellites play a role similar to the stars in constellations, and we have knowledge of where they are supposed to be at any given time. Ground stations use radar to verify their actual positions, ensuring they are where we expect them to be.[5] Receivers, like the ones in our phones or our parents' cars, constantly listen for signals from these satellites. These receivers determine how far away they are from some of these satellites. When the receiver calculates its distance from four or more satellites, it can pinpoint our exact location. From miles above in space, our position on the ground can be determined with remarkable accuracy! Typically, they can figure out our location within a few yards of where we actually are. More advanced receivers, however, can pinpoint our location to within a few inches! Ancient sailors from history would be amazed at how quickly and easily we can determine our location today. In 1973, the US Department of Defense launched GPS under the name NAVSTAR, exclusively for defense and military purposes, with no provisions for civilian use. In the 1980s, limited and selective civilian use was permitted. However, starting from 2000, GPS became common practice for the general public's benefit. A complete constellation of 24 satellites was placed in orbit by 1995, following the launch of the first prototype satellite by the US Government in 1978, with an additional 23 satellites added in the subsequent years. Consequently, in 2000, it became fully operational for public use. The space segment consists of a constellation of satellites, usually 24 to 32, which orbit the Earth in a circular path. The GPS system is comprised of a total of 27 satellites, of which 24 are in operation, and 3 additional satellites are kept on standby in case any of the 24 operational satellites encounter functional issues.[6]

With this expanded constellation, nine satellites are visible at all times, significantly enhancing reliability and accuracy. Through the control segment, we can oversee and manage ground stations that capture the radio signals sent by the various satellites. The control segment also synchronizes atomic clocks to ensure precise readings. This synchronization enables the adjustment of the satellite's orbit path. The user segment consists of the receiver, which uses the transmitted data to estimate the user's exact location. The user's capability is determined by the number of satellites it can monitor simultaneously, referred to as "Channels." Notably, there have been substantial improvements in recent years, and the available number of channels can now range from 12 to 20, a considerable increase from the initial limit of just 4 or 5. Trilateration remains the process of calculating the distance between the receiver and each satellite separately. This aids in determining the precise point where these distances intersect, allowing for accurate receiver location estimation. Furthermore, a greater number of satellites in the receiver's view results in higher location accuracy. Typically, a receiver on Earth has at least four GPS satellites within its line of sight. The GPS transmitter sends information about position and time to the receiver at fixed intervals. These signals transmitted to the receiver are in the form of radio waves.[7] By measuring the time difference between when the GPS satellite sends the signal and when the GPS receiver receives it, the distance between the GPS receiver and the satellite can be determined. Utilizing the trilateration process, the receiver establishes its location based on signals received from at least three satellites. For calculating a 2D position, which includes latitude and longitude, a minimum of 3 satellites are required. To determine a 3D position, which includes latitude, longitude, and altitude, at least 4 satellites are necessary. Today, the system integrates GPS, GLONASS, Galileo, BeiDou, and other regional systems as part of the standard practice. In fact, it enables the interchangeable use of these location services, offering multi-signal capabilities for receivers. This is an analytical paper that examines and portrays the satellite and communication system. It covers the background of Earth's orbit and satellites, the history and operating principles of GPS, its applications, market demand, and briefly evaluates other global and regional NSS systems.

Background of Earth Orbit and Satellite

The use of satellites for direction finding, steering, mapping, course plotting, or navigation has brought about a big change in the world. It has opened up new opportunities in many sectors that need highly accurate positioning, even for everyday personal use. The range of possible uses has grown a lot in the last ten years, bringing unique benefits in areas like society, economy, technology, military, business, and the environment. Some of these uses, even though they can technically work with the current GPS system, face several problems, especially in terms of reliability, precision, and making sure things are correct. The most basic issues come from two important aspects that are very necessary in many cases: being accurate and available, and making sure things are correct

Medium Earth Orbit (MEO). A Medium Earth Orbit (MEO) is an orbit that goes around Earth, and it's higher up than a Low Earth Orbit (LEO) but lower than a High Earth Orbit (HEO). It's at an altitude between 2,000 and 35,786 kilometers (or 1,243 and 22,236 miles) above sea level. It is also called a mid-Earth orbit or an intermediate circular orbit (ICO).[8] Again, when we talk about a geocentric orbit, Earth-centered orbit, or Earth orbit, we mean any object going around Earth, like the Moon or human-made satellites. In 1997, NASA estimated that there were about 2,465 artificial satellite payloads going around Earth, along with 6,216 pieces of space junk [9], all tracked by the Goddard Space Flight Center.[10] Over 16,291 objects[11] launched before have fallen back to Earth.[12] Earth's atmosphere is the layer of gases, called air, held in place by Earth's gravity that surrounds our planet, forming the planet's

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atmosphere.[13] Earth's atmosphere does a few important things: it creates pressure, takes in most small space rocks and the Sun's strong rays, keeps things warm by holding onto heat (known as the greenhouse effect), which allows for life and liquid water on Earth, and it makes the temperature differences between day and night less extreme.[14] As of 2023, if we look at the mole fraction in dry air, it's contains about 78.08% nitrogen, 20.95% oxygen, 0.93% argon, 0.04% carbon dioxide, and a bit of other gases. [15]

A spacecraft gets into orbit when its centripetal acceleration,[16] caused by gravity, is not more than the centrifugal acceleration due to its horizontal velocity component.[17] For a Low Earth Orbit (LEO), this velocity clocks in at approximately 7,800 meters per second (or 28,100 kilometers per hour, which is about 17,400 miles per hour). However, the fastest speed ever reached by a crewed airplane was 2,200 meters per second (7,900 kilometers per hour, or 4,900 miles per hour) back in 1967 by the North American X-15.[18] To reach the Earth's orbital velocity at an altitude of 600 kilometers (about 370 miles), you need about 36 MJ per kilogram of energy. This amount is six times more than what you'd need just to climb up to that same altitude.[19] When a spacecraft's perigee, the point in its orbit closest to Earth, dips below approximately 2,000 kilometers (or 1,200 miles), it starts to experience drag from the Earth's atmosphere. This drag lowers its orbital altitude.[20] The rate at which this orbital decay occurs depends on the satellite's size and mass, as well as variations in the air density of the upper atmosphere.The decay becomes more rapid below 300 km when lifetime is only matter of days.[21] Once a satellite descends to 180 kilometers (around 110 miles), it only has a few hours before it burns up in the atmosphere.[22] To completely break free from Earth's gravitational pull and venture into interplanetary space, you'd need an escape velocity of about 11,200 meters per second (or 40,300 kilometers per hour, which is approximately 25,100 miles per hour).[23,24]

The distinction between Medium Earth Orbit (MEO) and Low Earth Orbit (LEO) is a height we pick by common agreement. In contrast, the line between MEO and High Earth Orbit (HEO) is the specific height of a geosynchronous orbit.[25] In this orbit, a satellite takes 24 hours to go all around the Earth, which is the same time Earth itself rotates.[26] However, this geosynchronous orbit is an orbit around Earth where it takes precisely 23 hours, 56 minutes, and 4 seconds [27] (one sidereal day) to complete one orbit, matching Earth's rotation.[28] Because of this synchronized rotation and orbital period, to an observer on Earth, an object in a geosynchronous orbit returns to the exact same spot in the sky after one sidereal day.[29] During the day, the object's position in the sky may appear still or follow a path, often forming a figure-8 shape. The exact characteristics of this path depend on the orbit's tilt and shape.[30] A circular geosynchronous orbit maintains a steady height of 35,786 kilometers (22,236 miles).[31] So, geosynchronous satellites orbit Earth in sync with a sidereal day.[32] To someone fixed on Earth's surface, they trace paths that repeat daily, creating recognizable patterns known as analemmas.[33] These paths are generally elliptical, teardrop-shaped, or figure-8 in form.[34] Their exact shapes and sizes depend on the orbit's parameters. Some of these geosynchronous satellites are geostationary. Ideally, they have perfectly round orbits, aligned with Earth's equator.[35] A geostationary satellite should appear stationary relative to Earth's surface, staying above a single point on the equator.[36] However, no real satellite is entirely geostationary. Instead, real ones trace small analemmas in the sky.[37] Since geosynchronous satellite orbits are close in size to Earth and substantial parallax happens, the analemmas appear different depending on where an observer is located on Earth's surface. This causes observers in various places to see distinct analemmas.

All the satellites found in MEO complete their orbits in less than 24 hours.[38] The shortest period for a circular orbit at the lowest MEO height is about 2 hours.[39] These MEO satellites face influences from things like the sun's radiation push, which is the strongest non-gravitational force acting on them.[40] Other forces that affect them include the reflection of sunlight from Earth (albedo),[41] thrust from navigation antennas, and heat-related effects due to radiation.[42] In the MEO zone, there are two regions above the equator where there are energetic charged particles known as the Van Allen radiation belts. These particles can harm the electronic systems of satellites unless they have special protection.[43] Among the MEO orbits, two are especially important. One is the semi-synchronous orbit, located around 20,200 kilometers (about 12,600 miles) high. Satellites in this orbit take 12 hours to complete an orbit and pass over the same two spots on the equator every day.[44] This predictable orbit is what the GPS uses in the United States (US).[45] Other navigation satellite systems, like GLONASS from Russia (at an altitude of 19,100 kilometers or 11,900 miles),[46] Galileo from the European Union (at an altitude of 23,222 kilometers or 14,429 miles),[47] and BeiDou from China (at an altitude of 21,528 kilometers or 13,377 miles),[48] also use similar MEO orbits. Then there's the Molniya orbit, which has a high tilt of 63.4 degrees and a significant deviation from a perfect circle (eccentricity of 0.722).[49] Satellites in this orbit take 12 hours to complete an orbit and spend most of their time over high northern latitudes. This type of orbit is well-suited for communications in regions like Russia, Canada, and Greenland, which are located at high northern latitudes.[50] With an apogee (the highest point in its orbit) as high as 40,000 kilometers (about 25,000 miles) and an apogee sub-satellite point at 63.4 degrees north, satellites in this orbit have excellent visibility in the northern hemisphere, covering Russia, northern Europe, Greenland, and Canada.[51] In MEO, we also find communication satellites like the O3b and the upcoming O3b mPOWER[52]constellations. They're used for telecommunications and data backhaul to maritime, airborne, and remote locations. These satellites orbit at an altitude of 8,063 kilometers (about 5,010 miles).[53] MEO is also chosen for communication satellites that provide coverage for the North and South Poles.[54] An early example of a satellite in MEO is Telstar 1, an experimental communication satellite launched in 1962.[55] In May 2022, a Kazakhstani mobile network operator called Kcell, along with satellite owner and operator SES, demonstrated the use of SES's O3b MEO satellite constellation[56] to provide high-speed mobile internet to remote areas of Kazakhstan. This allowed for reliable video calls, conferences, streaming, and web browsing, with a five times lower delay compared to the existing platform based on geostationary orbit satellites.[57]

Low Earth Orbit (LEO). Low Earth Orbit (LEO) is a special way things move around our planet. It means they go around Earth pretty fast, finishing more than 11 rounds every day and an eccentricity less than 0.25.[58] These paths are not too stretched out or squished, kind of like an oval. LEO is where most human-made things in space hang out,[59] and they don't go too far from Earth—about one-third of Earth's size above its surface.[60] Additionally, the term "LEO region" refers to the space below an altitude of 2,000 km (1,200 mi), approximately one-third of Earth's radius.[61] Objects in orbits that pass through this zone, whether they reach higher points or are partially in orbit,[62] are closely monitored. This is because they pose a collision risk to the numerous satellites in Low Earth Orbit (LEO).[63] Every manned space station that has existed so far has been located within Low Earth Orbit (LEO). However, during the period from 1968 to 1972, the Apollo program's missions to the moon took astronauts beyond LEO.[64] After the conclusion of the Apollo program, there have been no human spaceflights that ventured beyond Low Earth Orbit (LEO).[65]Some sources define the LEO region as the area in space where Low Earth Orbit (LEO) satellites are positioned.[66] Certain highly elliptical orbits might intersect the LEO region at their lowest point but don't qualify as Low Earth Orbit (LEO) because their highest point or apogee goes beyond 2,000 km (1,200 mi).[67] Sub-orbital objects can enter the LEO region momentarily, but they don't maintain an LEO orbit because they eventually re-enter the Earth's atmosphere.[68] Distinguishing between LEO orbits and the LEO region becomes crucial when analyzing potential collisions involving objects that might not be in LEO but could still crash into satellites or debris in LEO orbits. To maintain a stable low Earth orbit, an object needs to travel at an average orbital velocity of about 7.8 km/s (4.8 mi/s), which equals 28,000 km/h (17,000 mph). However, this velocity requirement varies depending on the specific altitude of the orbit. For example, for a circular orbit at 200 km (120 mi) above Earth, the needed orbital velocity is 7.79 km/s (4.84 mi/s), whereas for a higher 1,500 km (930 mi) orbit, the velocity is reduced to 7.12 km/s (4.42 mi/s).[69] To reach a low Earth orbit, the launch vehicle typically requires a delta-v of approximately 9.4 km/s (5.8 mi/s).

In Low Earth Orbit (LEO), the force of gravity is only slightly weaker compared to the surface of the Earth. This happens because LEO is much closer to the Earth's surface than the Earth's overall radius. However, objects in orbit are actually in a continuous state of free fall around the Earth. This is because in orbit, the gravitational force pulling them inward is perfectly balanced by the outward centrifugal force, creating a stable equilibrium.[70] Consequently, spacecraft in orbit remain in orbit, and individuals inside or outside these spacecraft consistently encounter a sensation of weightlessness. Objects in Low Earth Orbit (LEO) encounter resistance from gases in the thermosphere (which starts around 80–600 km above the surface) or the exosphere (which is approximately 600 km or 400 mi and higher), depending on the altitude of their orbit.[71] Satellites in orbits that go below 300 km (190 mi) altitude quickly lose altitude because of atmospheric drag. Equatorial Low Earth Orbits (ELEO) are a specific type of Low Earth Orbit (LEO). These orbits have a low angle compared to the Equator, which lets them revisit low-latitude areas on Earth rapidly. They also require the least amount of delta-v to maintain their orbit, but this is only the case if they align directly with the Earth's rotation. On the other hand, orbits with very steep angles compared to the Equator are often called polar orbits or Sun-synchronous orbits.[72] Higher orbits include Medium Earth Orbit (MEO), and even higher up, we have the Geostationary Orbit (GEO).[73] Orbits positioned higher than those in low orbit can pose a risk of damaging electronic components prematurely due to high levels of radiation and the buildup of electrical charge. In 2017, a new category known as Very Low Earth Orbits (VLEO) started appearing in official filings and regulations. These orbits are located at altitudes below approximately 450 km (280 mi)[74] and demand the application of innovative technologies to maintain their position since they typically degrade too quickly to be economically practical.[75]

A low Earth orbit, known as LEO, is the most energy-efficient place to put satellites. It offers fast communication with a lot of data capacity and minimal delay. Satellites and space stations in LEO are easier to reach for maintenance and crew missions. Because it takes less energy to put a satellite into LEO and they don't need super powerful equipment for communication, LEO is commonly used for various communication purposes, like the Iridium phone system.[76] Certain communication satellites operate in much higher orbits known as geostationary orbits. They move at the same speed as the Earth's rotation, which makes them seem stationary above a fixed spot on the planet. In contrast, the International Space Station (ISS) is situated in a Low Earth Orbit (LEO), roughly 400 km (250 mi) to 420 km (260 mi) above the Earth's surface. To counter the effects of orbital decay, the ISS requires periodic boosts a few times each year.[77] Iridium telecom satellites circle the Earth at an altitude of approximately 780 km (480 mi). For Earth observation purposes, including spy and other imaging satellites, they prefer Low Earth Orbit (LEO) because being closer to Earth allows for clearer surface observation. Most man-made satellites are positioned in LEO.[78] Satellites can also make use of steady sunlight on the ground by following Sun-synchronous Low Earth Orbits (LEO) positioned at an altitude of around 800 km (500 mi) with a nearly polar angle.[79] The Hubble Space Telescope revolves at an altitude of approximately 540 km (340 mi) above the Earth's surface.[80] The Chinese Tiangong space station was sent into orbit in April 2021 and is presently circling the Earth at altitudes ranging from about 340 km (210 mi) to 450 km (280 mi).[81]In contrast to geosynchronous satellites, satellites in Low Earth Orbit (LEO) have a limited field of view, allowing them to observe and communicate with only a portion of the Earth at any given moment.[82] As a result, a network or group of satellites is needed to ensure uninterrupted coverage.[83] Satellites in the lower parts of Low Earth Orbit (LEO) experience rapid orbital decay. To keep a stable orbit, they need either regular boosts or the launch of new satellites when the old ones re-enter the Earth's atmosphere.[84]

High Earth Orbit (HEO). HEO is a space region encircling Earth where satellites and spacecraft are positioned in orbits far above the Earth's atmosphere.[85] This region is characterized by an altitude exceeding 35,786 km (22,236 mi) above sea level, equivalent to the radius of a circular geosynchronous orbit.[86] HEO stretches out to the outer limits of Earth's sphere of influence.[87] Satellites in HEO serve various purposes, including communication, navigation, scientific research,[88]and military applications.[89,90] Several satellites, like TESS,[91] have been positioned in HEO. One of the significant advantages of HEO is that it offers an almost unobstructed view of both Earth and deep space. This makes it an excellent spot for astronomical observations and monitoring our planet. Furthermore, satellites in HEO can offer uninterrupted coverage of the Earth's surface, which is highly valuable for communication and navigation applications.[92] There are four primary reasons why the majority of satellites are positioned in lower orbits. First, High Earth Orbits (HEO) can take a month or even longer to complete a single orbit. This extended duration is because HEOs cover vast distances and travel at a relatively slower speed of only 7,000 mph. In contrast, Low Earth Orbits (LEO) can complete an orbit in less than 90 minutes.[93] Therefore, HEO is not suitable for satellites that require rapid orbiting. Second, HEOs demand significantly more energy for satellite placement compared to LEOs.

Placing a satellite into High Earth Orbit (HEO) requires nearly as much energy as putting it into a heliocentric orbit.[94] As an illustration, a used Falcon 9 rocket can transport 50,000 pounds to Low Earth Orbit (LEO). However, it can only carry approximately 10,000 pounds to High Earth Orbit (HEO).[95] This results in a cost that is five times higher to position a payload in HEO compared to placing it in LEO. Third, HEOs are extremely distant from Earth, leading to a persistent communication delay when transmitting signals to and from the satellite. This delay occurs because signals can only travel at the speed of light.[96] This implies that there can be a delay time of approximately 0.1 to 4.5 seconds for each signal transmission. Such delays render it impractical for internet usage and challenging for various other applications as well.[97] The fourth reason is radiation. HEO exists beyond Earth's magnetic field.[98] This results in a significantly higher level of radiation in HEO. Consequently, spacecraft in HEO need special equipment and protective shielding to safeguard them from this radiation.[99] Consequently, only satellites with specific needs that can benefit from the distinct features of HEO choose to utilize this orbit. The advancement of HEO technology has made a substantial contribution to space exploration and has laid the foundation for upcoming missions into deep space.[100] The capability to position satellites in HEO has empowered scientists to achieve groundbreaking breakthroughs in the fields of astronomy and Earth science. It has also played a pivotal role in facilitating global communication and navigation systems.[101]

Global Navigation Satellite System (GNSS)

A Global Navigation Satellite System, abbreviated as GNSS, comprises a constellation of satellites that transmit timing and orbital data. This information serves the purpose of navigation and accurately determining the position of an object. In the context of Windward, GNSS is employed to ascertain the location of a vessel.[102] GNSS technology measures three essential aspects: the precise location of an object, its speed, and timing. When equipped with the appropriate technology, GNSS achieves remarkable accuracy. Various GNSS applications find utility in military, commercial, and private domains.[103] These applications cover a wide range of uses, including navigation systems, tracking, scientific research, telecommunications, emergency response, and more. GNSS technology is even utilized by dog owners to prevent their pets from getting lost. The precision of GNSS can be explained through the following three measurements.

- Location: accurate within millimeters
- Speed: User range rate error (URRE) of ≤0.006 m/sec over any 3-second period
- Timing: ≤30 nanoseconds (billionths of a second)

In fact, GNSS systems consist of three key components. The first element is the space segment, which comprises a network of satellites, known as constellations, orbiting approximately 20,000 kilometers above Earth. Each satellite within the GNSS constellation emits a signal that carries its identification and shares information about its time, orbit, and status. The second element of GNSS is the control segment, operated by an earth-based network of ground control stations functioning as GNSS receivers. These ground control stations analyze the signals they receive and relay orbit and time corrections to the satellites within the constellation through data uploading stations. The third element of GNSS is the user segment, which pertains to the device, such as a smartphone or receiver, that is integrated into the vessel being tracked.[104] GNSS systems that offer improved accuracy and integrity monitoring suitable for civilian navigation are categorized as follows.[105]

- **GNSS-1** is the first-generation system that brings together existing satellite navigation systems like GPS and GLONASS along with either SBAS or GBAS. In the United States, the satellite part is called WAAS, in Europe, it's EGNOS, and in Japan, it's MSAS. To make it even more accurate, they use systems on the ground, like the Local Area Augmentation System (LAAS).[106]
- **GNSS-2** represents the second generation of systems that autonomously offer a complete civilian satellite navigation system, illustrated by the European Galileo positioning system. These systems will deliver the accuracy and integrity monitoring essential for civilian navigation, including aircraft. Initially, this system exclusively comprised Upper L Band frequency sets (L1 for GPS, E1 for Galileo, and G1 for GLONASS).[107] In recent times, GNSS systems have started employing Lower L Band frequency sets (L2 and L5 for GPS, E5a and E5b for Galileo, and G3 for GLONASS) for civilian applications. These frequencies offer enhanced

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overall accuracy and are less susceptible to issues related to signal reflection.[108] As of the latter part of 2018, some consumer-grade GNSS devices have become available that utilize both of these frequency sets. These devices are often referred to as 'Dual-band GNSS' or 'Dual-band GPS' devices. Due to the fact that numerous global GNSS systems and augmentation systems utilize frequencies and signals in the vicinity of L1, there has been a production of 'Multi-GNSS' receivers capable of utilizing multiple systems.[109] While certain systems make efforts to achieve the highest possible interoperability with GPS by offering the same clock, others do not do so.

GNSS stands as an exceptionally precise positioning system. The accuracy of GNSS can change based on how good the device is and the environment it's used in. But in perfect conditions, it can find something very precisely, within a few centimeters. It's most accurate when you use special GNSS devices or systems that have two frequencies and when you're outside where nothing is blocking the signals. In contrast, a typical smartphone offers accuracy within a 5-meter radius. Many things can make GNSS less accurate. Things like buildings, bridges, and trees can block the signals and make it harder to get the right location. When you're inside a building or underground, GNSS doesn't work well. Sometimes, the signals bounce off buildings, or there are big solar storms, or the satellites need maintenance, and that messes up the accuracy too. Also, sometimes GNSS measurements are right, but the maps or the data about roads, businesses, or addresses are wrong, which can make it seem like GNSS is not working well. Currently, there are four primary GNSS constellations in operation, along with two regional ones. They are as follows.

- Global Positioning System (GPS), United States (US)
- Global Navigation Satellite System (GLONASS), Russia
- Galileo, European Union (EU)
- BeiDou Navigation Satellite System (BDS), China
- Indian Regional Navigation Satellite System (IRNSS), India
- Quasi-Zenith Satellite System (QZSS), Japan

Historical Background of NAVSTAR GPS

The NAVSTAR 1 Global Positioning System (GPS) was the very first satellite navigation system. It allowed people to find their exact location in three dimensions and measure time very accurately, down to billionths of a second. This system went from an idea to a fully working system in just over 20 years.[110] However, it's important to note that convincing others of the idea wasn't a simple task. In the late 1960s and early 1970s, a man named Ivan Getting, who was the President of the Aerospace Corporation and one of the GPS pioneers, had an idea. He talked to Lee DuBridge, who was working as President Richard Nixon's science advisor, and said they should make a special group (like a team) led by the President to figure out how to make satellite navigation better because many people could use it. After thinking about it for a while, DuBridge decided that making this idea happen would be too hard. He told Getting, "there are too many people, too many bureaucracies, too much politics, and too many agencies involved. Why don't you just have the Air Force develop it the way we always did?"[111] Around 1972, both the U.S. Air Force (USAF) and the U.S. Navy had been trying to make satellite-based navigation better for a few years. GPS got help from three other systems or programs before it came along. There was one called Transit, which was also known as the Naval Navigation Satellite System, made by the Johns Hopkins University Applied Physics Laboratory (APL). Then there was the 'Timation Satellite' program from the Naval Research Laboratory, led by Roger Easton. The USAF had a project called 621B. All of these things played a part in creating GPS. These early initiatives played a significant role in the development of GPS.

In 1973, Colonel Bradford Parkinson was leading the Joint Program Office (JPO) for GPS in the U.S. Air Force. During the Labor Day weekend, he got about twelve JPO members together. He told them to come up with a plan for a completely new satellite navigation system. He wanted them to use the best ideas and technology that were available at that time to make it happen.[112] After that, GPS started to come together steadily. By June 1974, the JPO picked Rockwell International to build the satellites. They also set up the first control center at the Army's Yuma Proving Ground in Arizona. In February 1978, they sent the first working prototype into space. Then, in February 1989, the U.S. Air Force launched the first fully working Block 2 version of GPS, which marked a significant milestone in its development.[113] Even though they had 24 Block 2 satellites by December 1993, GPS wasn't officially completely ready until April 1995. Creating the whole system cost between US$10 and US$ 12 billion, and the U.S. Air Force thought it cost about US$400 million every year to maintain the basic GPS services.[114] The main reasons for making GPS were to make sure that weapons could be very accurate and to reduce the use of many different navigation systems in the U.S. military.

From the beginning, the Department of Defense (DOD) knew that GPS could be useful for people worldwide. To keep enemies from using it with full accuracy, the U.S. Air Force added a protective feature called 'selective availability' (SA). This feature gave the U.S. military and its friends more accurate satellite signals than everyone else got. But there was a big event in 1983 when a Korean Airline flight went the wrong way and was shot down by Soviet fighters. After that, President Ronald Reagan said that the less accurate GPS signal would always be free for everyone when GPS was fully ready. In the early 1990s, GPS was improving, and people with GPS devices wanted more accuracy. GPS device makers started working with other companies in areas like communication and computing because they saw many ways to use it. Finally, in May 2000, President William Clinton realized how

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useful GPS was worldwide and decided to stop using SA. This gave millions of non-military users access to the more accurate GPS signals.[115] As people wanted more accuracy from GPS, they came up with ways to improve it. For smaller areas, they used pseudolites, which are ground-based transmitters that send out signals like GPS. They also used something called differential GPS (DGPS), which required a really good GPS receiver at a known spot that had been measured and mapped carefully.[116]

The use of a Wide Area DGPS (WADGPS), which involves multiple reference receivers at multiple monitor stations and a central control station, will allow similar results to be achieved over a larger area. WADGPS, for example, included the Wide Area Augmentation System (WAAS), which the Federal Aviation Administration (FAA) believed would eventually be able to rely on GPS for navigation with confidence and safety as the primary navigation system due to its integrity, reliability, and availability of time.[117] The National Geodetic Survey (NGS) coordinated a network of continuously operating reference stations (CORS) across the United States by 2006, enhancing GPS services to millions of users.[118] In parallel, other countries and geographic regions began developing their own GPS augmentation systems, such as the European Geostationary navigation overlay System (EGNOS), India's GPS and Geostationary Augmentation network (GAGAN), Australia's Ground-based regional Augmentation System (GRAS), and Japan's Multi-transport Satellite Augmentation System (MSAS).[119] In addition to the United States' Global Positioning System (GPS), Russia operated its own Global Navigation Satellite System (GLONASS), China experimented with its BeiDou navigation satellites, and Europe pressed hard toward launching the Galileo satellite navigation system. Whether these capabilities could be combined into a fully integrated global navigation satellite system (GNSS) remained a question without an immediate answer, but the military, civil, and commercial utility of GPS was unquestionable. The societal impact of GPS is vast and far-reaching, and a full accounting of it would require hundreds of pages.[120] However, a few interesting facts about GPS satellites are as follows:

- The official nomenclature employed by the United States Department of Defense for the Global Positioning System (GPS) is NAVSTAR.
- Initiated in the year 1978, the inaugural GPS satellite was successfully launched.
- The full constellation of 24 GPS satellites was operational by 1994.
- The design life of a GPS satellite is approximately 10 years. To ensure the continued availability of the constellation, replacement satellites are being built and launched on a regular basis.
- A GPS satellite weighs approximately 2,000 pounds and is about 17 feet across when its solar panels are extended.
- GPS satellites are primarily powered by solar energy, but they have backup batteries on board to provide power during periods of darkness, such as during a solar eclipse.
- The transmitter power of a GPS satellite is typically 50 watts or less.
- The GPS space segment consists of 31 satellites that are orbiting the Earth at an altitude of about 12,000 miles.
- These satellites are constantly moving, completing two orbits around the Earth in less than 24 hours.
- The GPS satellites travel at a speed of approximately 7,000 miles per hour. This is necessary to maintain their position in orbit.
- The third generation of GPS satellites, known as Block III, is currently being deployed.

Working Principal of GPS

GPS satellites are constantly moving, orbiting the Earth twice every 24 hours. They transmit unique signals and orbital parameters that can be decoded by GPS devices to determine their location. GPS receivers use the information and trilateration to find a user's exact location. Satellite navigation uses a global network of satellites that transmit radio signals from medium Earth orbit to find a user's location. The GPS is the most familiar constellation for satellite navigation users, with 31 satellites developed and operated by the United States. There are also three other constellations that provide similar services. As a whole, these constellations and their augmentations are called Global Navigation Satellite Systems (GNSS). In addition to GPS, there are three other constellations that provide similar services: GLONASS, Galileo and BeiDou. All of these constellations are operated by their respective governments, but they offer free access to their signals to the international community. All providers have developed ICAO Standards and Recommended Practices (SARPs) to support the use of their constellations for aviation.[121] GPS function in 3D view is shown in this YouTube ref.[122]

95% of the time, the basic GPS service gives users an accuracy of about 7.0 meters anywhere on or near the surface of the earth. Each of the 31 satellites emits signals that, when combined with signals from at least four other satellites, enable receivers to detect their location and time. Atomic clocks on board GPS satellites provide extremely accurate time. In order for a receiver to continuously know what time the signal was broadcast, the time information is included in the codes that the satellite broadcasts. The signal contains information that a receiver can use to determine the satellites' positions and make other necessary adjustments for precise positioning. The receiver determines the distance, or range, from the receiver to the satellite using the time difference between the time of signal reception and the broadcast time. The ionosphere and the troposphere can cause delays in signal propagation or decreases in signal speed, which the receiver must take into account. The receiver can calculate its own three-dimensional position using knowledge of the distances to three satellites and the location of the satellite at the time the signal was sent. Calculation of

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ranges from these three signals needs an atomic clock synchronized to GPS. The receiver performs the requirement for an atomic clock, by taking a reading from a fourth satellite. Thus, the receiver uses four satellites to compute latitude, longitude, altitude, and time.[123] GPS provides two types of services.

- SPS (Standard Positioning System): Where Frequency is 1575.42 MHz. Open for all users worldwide. C/A Code.
- PPS (Précised Positing System): Where Frequency is 1227.60 MHz. Encrypted data restricted for US Military and Marine Corps uses.

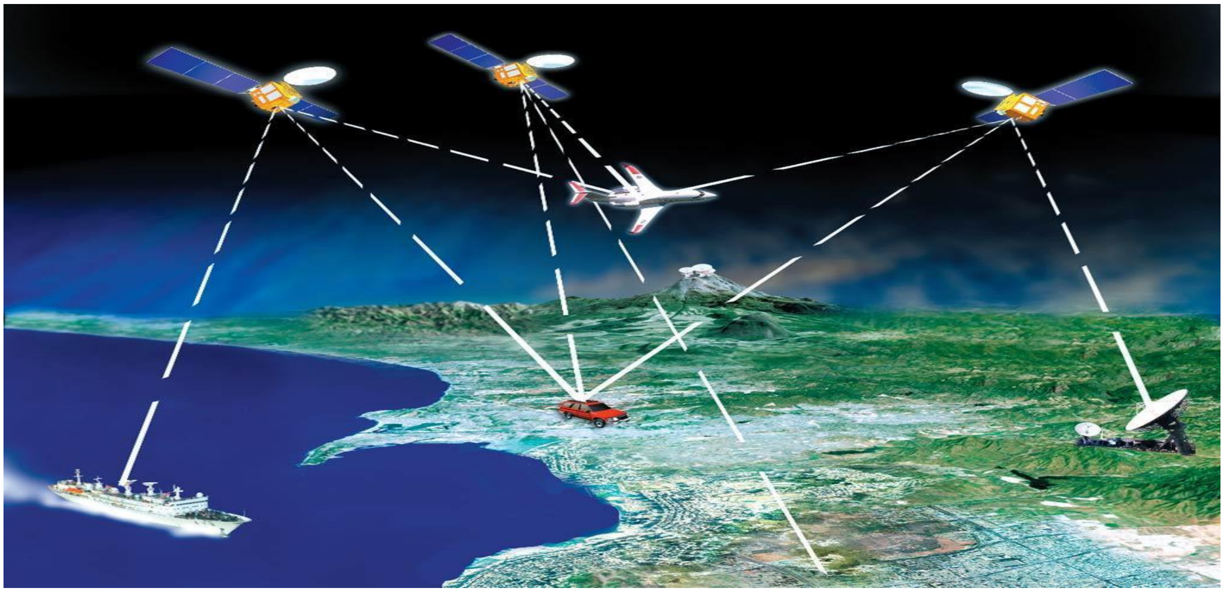

Figure 1: GPS provides different types of services worldwide[124]

Calculation of User Position

In order to determine user position in three dimensions $(x_u{}'y_u{}'z_u)$ and the offset t_u 'pseudorange measurements are made to four satellites which results in the following equations:

$$\rho_j = \|s_j - u\| + ct_u{}'$$

Where j ranges from 1 to 4 and references the satellites. Equation (2.19) can be expanded into the following set of equations in the unknowns $x_u{}'y_u{}'z_u{}'$ and $t_u{}'$:

$$\rho_1 = \sqrt{}(x_1 - x_u)^2 + (y_1 - y_u)^2 + (z_1 - z_u)^2 + ct_u$$

$$\rho_2 = \sqrt{}(x_2 - x_u)^2 + (y_2 - y_u)^2 + (z_2 - z_u)^2 + ct_u$$

$$\rho_3 = \sqrt{}(x_3 - x_u)^2 + (y_3 - y_u)^2 + (z_3 - z_u)^2 + ct_u$$

$$\rho_4 = \sqrt{}(x_4 - x_u)^2 + (y_4 - y_u)^2 + (z_4 - z_u)^2 + ct_u$$

Where $x_j{}'y_j{}'$ and $z_j{}'$ denote the jth satellite's position in three dimensions.

GPS and its Accuracy

At least 24 operational satellites make up the Global Positioning System (GPS), a satellite-based navigation system used by the US government. Satellites behave like the stars in constellations, and we always know where they should be. Radar is used by the ground stations to confirm that they are where we think they are. A receiver, similar to the one we might find in our phone or our parents' car, is always looking for a signal from these satellites. The receiver calculates their distance from some of them. Once the receiver determines how far away it is from four or more satellites, it can pinpoint our location. Our location on the ground can be pinpointed with great accuracy from miles in space. They can usually discover us within a few yards of where we actually are. Nevertheless, more sophisticated receivers can pinpoint our position to within a few inches. The speed and simplicity with which we can now locate ourselves would astonish the ancient sailors of ancient time.[125] GPS is a system. It's made up of three parts: satellites, ground stations, and receivers. GPS works in any weather conditions, anywhere in the world, 24 hours a day, with no subscription fees or setup charges. The U.S. Department of Defense (USDOD) originally put the satellites into orbit for military use, but they were made available for civilian use in the 1980s.

In a precise orbit, GPS satellites make two daily orbits around the earth. GPS receivers can decode and calculate the precise location of a satellite largely owing to the distinctive signals and orbital parameters that each satellite transmits. This data and trilateration are used by GPS receivers to determine a user's precise location. The time it takes to receive a transmitted signal is basically how the GPS

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receiver determines the distance to each satellite. The receiver can detect a user and electronically display their position to measure their running route, map a golf course, find their way home, or navigate anywhere in a store, shop, hospital, station, etc.[126] Today, GPS is a standard feature in a wide range of gadgets, including smart watches, satellite communicators, cars, boats, and more. The signal from at least three satellites must be locked onto by a GPS receiver in order to calculate our 2D position (both latitude and longitude) and track movement. The receiver can calculate our three-dimensional position (including latitude, longitude, and altitude) when four or more satellites are visible. A GPS receiver will typically track eight or more satellites, but this will vary depending on the time of day and our location on the planet. Some gadgets allow you to perform all of that from your wrist.[127] After determining our position, the GPS device can calculate a variety of other data points, including: speed, bearing, track, trip distance, distance to destination, sunrise and sunset times, and many more.

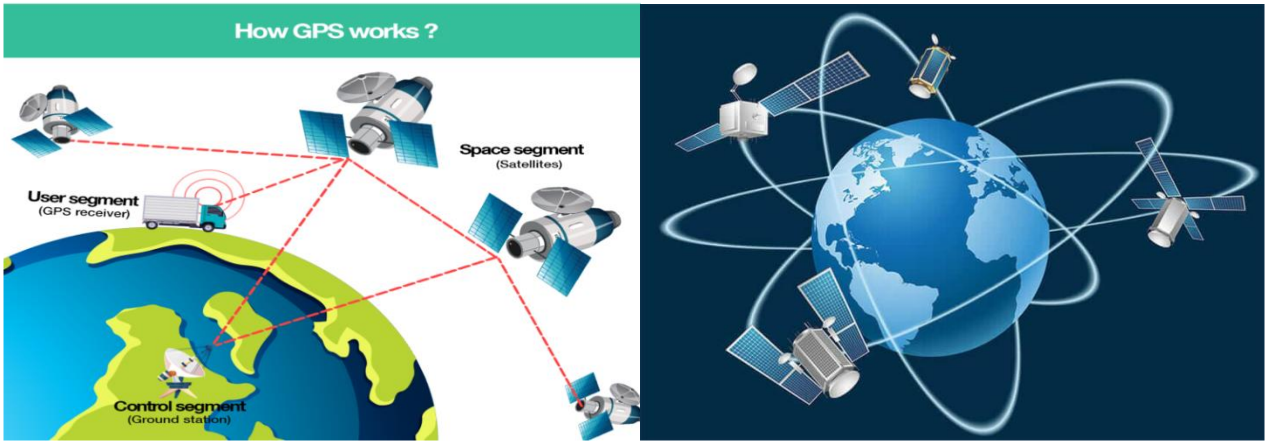

Figure 2: Working principal of GPS[128] and origin of GPS[129]

Parallel multichannel designs are a key factor in the high accuracy of today's GPS receivers. Our receivers are capable of rapidly acquiring satellite signals. They are also capable of maintaining tracking locks in challenging environments, such as dense tree cover or urban settings with tall buildings. Atmospheric factors and other error sources can affect the accuracy of GPS receivers. The typical accuracy of Garmin GPS receivers is 10 meters. The accuracy of GPS receivers is improved on the water due to the lack of obstructions that can interfere with the signal.[130] WAAS constitutes a highly precise navigation system tailored for employment within civil aviation. The U.S. National Airspace System (NAS) did not have the ability to provide all users, precision approach horizontal and vertical navigation for all locations before the Wide Area Augmentation System (WAAS) was implemented. WAAS made this capability a reality. The Wide Area Augmentation System (WAAS) can improve the accuracy of GPS positioning to better than 3 meters by providing corrections for atmospheric and satellite position errors. WAAS receivers do not require any additional equipment or fees to use.[131] The Federal Aviation Administration (FAA) and the Department of Transportation are developing the WAAS to use in the precision flight approaches. At present, GPS does not meet the FAA's navigation requirements for accuracy, integrity, and availability. WAAS corrects for ionospheric disturbances, timing errors, and satellite orbit errors in GPS signals, and provides vital integrity information regarding the health of all the GPS satellites.[132]

Applications of GPS

Primarily, a GPS monitoring system will display the motion of an object wherein it is set up.[133] This system proves to be an important tool on a every day or sectors basis. The areas wherein we can use GPS have been shown below:

1. **Logistics:** The real-time location of each consignment can be traced and tracked, which can be used to estimate the delivery time and costs of the entire operation. This allows for the entire fleet to be managed and monitored from a single mobile-based application.
2. **Municipal Corporation:** It is possible to track the entire fleet of vehicles and keep track of all the assets owned by the corporation.
3. **Drones and UAVs**: Prevent any loss or theft related accident by locating and tracking your Unmanned Aerial Vehicles and drones.
4. **Heavy Equipment:** Keep an eye on the operational status of the entire vehicle fleet and deploy them as necessary, following a comprehensive and systematic approach.
5. **Rental Bikes and Cars:** The movement of each rented vehicle can be monitored by tracking and tracing its real-time location. This can be used to generate detailed billing information for customers which the customers cannot refute. This can also help to prevent theft and robbery.
6. **Delivery Monitoring:** Restaurants that deliver instant delivery services has the reequirement of monitoring their personnel for ensuring that the customers are satisfied and return to provide business in the future again.
7. **Position of Lost Vehicle:** Determining the location of the vehicle in case of any theft or robbery.
8. **Road Traffic Information:** GPS can be used to estimate the time it will take to reach a destination by analyzing traffic conditions.
9. **Passengers Information:** GPS can be used to provide passengers with information about the current and next stop in public transit systems.

10. **SAR Operation:** GPS can be use for search and rescue or SAR operation successfully. Search operations conducted by the defense and military services can use GPS. GPS can be used to conduct successful search and rescue or SAR operations. Defense and military services use GPS for SAR Operations.
11. **Navigation:** Location-based services (LBS) positioning and navigation is the most rapidly expanding area of GPS use for civil, commercial, and personal purposes.[134] Land-based users of GPS include automobile drivers, fleet managers of trucks, railroads, delivery vehicles, and public transportation; emergency responders such as ambulance, fire, and police; and recreational activities such as golfing, hunting, skiing, biking, and hiking.[135]
12. **Industry:** Industry analysts and entrepreneurs saw LBS as an emerging multibillion-dollar market when GPS receiver technology and cellular phones became more affordable in the mid-1990s. Only two automotive companies, General Motors (OnStar) and Mercedes (TeleAid), offered consumers telematic LBS by 2002.[136]
13. **Sports andGolf:** Golfing was one of the most prominent sport and recreational uses of GPS. In 1997, Darryl Sharp's Geodetic Services, Inc., began using GPS technology to create three-dimensional maps of premier golf courses in the United States. By May 2002, they had mapped 55 courses. Professional, amateur, and casual golfers all adopted GPS-aided technology to improve their performance. Course managers enthusiastically supported this demand by purchasing GPS-equipped golf carts.[137]GPS is also used in football and rugby to control and analyze the training load.[138]

Figure 3: Working principal of GPS[139] and using satellites, ground stations, and receivers by GPS[140]

14. **Firm and Agriculture**: The adoption of GPS technology in precision farming, also known as site-specific management, began in the early 1990s and swiftly evolved into a diverse range of applications. These encompassed activities such as nighttime planting and cultivation, precise identification of weed, insect, and disease infestations, variable-rate application of fertilizers and pesticides, prevention of skips or overlaps during fertilization, the monitoring and mapping of crop yields, as well as the accurate detection of crop damage caused by hail or drought.[141]

15. **Disaster Relief:** The utilization of GPS in tandem with GIS, cartographic mapping, and other advanced technologies demonstrated its advantages in disaster relief and recovery endeavors. Following the destructive impact of Hurricane Andrew on Florida in 1992, the Federal Emergency Management Agency (FEMA) engaged survey teams in an experimental project to assess the extent of damage using GPS/GIS technology, departing from the conventional approach of labor-intensive, house-by-house interviews for damage assessment.[142]

16. **Time Calculation:** Most individuals commonly associate GPS with navigation, often overlooking its valuable role in providing accurate time, time intervals, and frequency data. This is due to the fact that GPS receivers determine their location by simultaneously measuring signals from multiple GPS satellites, and as a result, each signal from each satellite includes information about the time of transmission.[143]
17. **Time Differences:** Wireless positioning and tracking systems also reap significant advantages from the precision of GPS timing. In the case of a caller's mobile device, for instance, its location can be determined by computing and triangulating the time disparities in signal arrival at cellular towers with precisely known positions.[144]

18. **Recreation:** Leisure is a fundamental aspect of human biology and psychology, as recreational pursuits are frequently undertaken for the sake of joy, amusement, or sheer pleasure, creating an enjoyable experience[145]. In modern times, GPS technology is effectively

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harnessed for recreational purposes, including activities like Geocaching, Geodashing, GPS drawing, waymarking, and various location-based mobile games such as Pokémon Go.[146]

19. **Reference frames:** Recreation constitutes a fundamental dimension of human biology and psychology, often pursued for the purpose of delight, amusement, or sheer gratification, resulting in pleasurable experiences.[147] In the contemporary era, GPS technology is skillfully employed for recreational pursuits, encompassing endeavors like Geocaching, Geodashing, GPS drawing, waymarking, and diverse location-based mobile games such as Pokémon Go.[148]

20. **Robotics:** Autonomous robots equipped with GPS sensors possess the capability to navigate independently, utilizing these sensors to compute crucial parameters such as latitude, longitude, time, velocity, and direction.[149]

21. **Surveying:** Surveyors rely on precise geographic coordinates to create maps and establish property boundaries, with GPS technology proving immensely valuable for these purposes.[150]

22. **Tectonics:** Tectonic investigations serve as critical tools for economic geologists in their quest to locate fossil fuels and deposits of metallic and non-metallic resources[151]. GPS technology plays a pivotal role in this context by facilitating the direct measurement of fault motion during earthquakes. Moreover, during periods between seismic events, GPS can be utilized to gauge crustal movement and deformation, aiding in the estimation of seismic strain accumulation for the development of seismic hazard maps.[152]

23. **Telematics:** Telematics represents an interdisciplinary domain that spans telecommunications, vehicular technologies (including road transport and road safety), electrical engineering (encompassing sensors and instrumentation, wireless communications, and more), as well as computer science (involving multimedia, the Internet, and related areas)[153]. Within the realm of automotive navigation systems, GPS technology is seamlessly integrated with computers and mobile communications technology to enhance navigation capabilities.[154]

18. **Military Applications of GPS.** The first weapon in the United States arsenal to utilize GPS navigation was the Conventional Air-Launched Cruise Missile (CALCM) or AGM-86C. Its development commenced in June 1986 when Boeing Company received a 12-month contract to rapidly convert existing CALCMs, which had shown inaccuracies resulting in the inadvertent bombing of the French embassy during Operation Eldorado Canyon, a night attack on Libya two months prior. A loosely integrated GPS system with the missile's existing inertial navigation system (INS) enabled Boeing to deliver the initial CALCMs to the US Air Force by June 1987. During the early stages of the air campaign for Operation Desert Storm in January 1991, seven B-52G bombers from Barksdale Air Force Base, Louisiana, deployed a total of 35 CALCMs against eight high-value targets in Iraq, achieving a remarkable success rate of 85 to 91 percent, including several precise hits.[155] Throughout the 1990s, the US military introduced a range of air-dropped munitions incorporating GPS technology to varying degrees. The Joint Direct Attack Munition (JDAM) was particularly notable, transforming conventional "dumb" bombs into high-precision ordnance capable of effectively destroying multiple targets, regardless of the time of day, weather conditions, or adverse circumstances. During Operation Allied Force, the NATO air campaign against Serbia in 1999, US B-2 Spirit bombers deployed over 500 JDAMs with remarkable success, leading military strategists to envision the potential obsolescence of unguided bombs.[156] Other GPS-assisted US aerial weapons introduced in the 1990s included the AGM-154 Joint Stand-off Weapon (JSOW), the AGM-130 air-to-surface missile, the BGM-109 Tomahawk cruise missile, and the SLAM-ER (Stand-off Land Attack Missile—Enhanced Response).[157]

Advanced Spinning-Vehicle Navigation (ASVN), a suite of technologies, paved the way for the integration of GPS/INS guidance into progressively smaller munitions. By 2001, the US Army had plans to incorporate ASVN into artillery shells, while the US Navy had similar intentions for rocket-assisted projectiles fired from its deck guns. A significant milestone occurred when the Army's 155-mm Xm982 Excalibur round, fired from a howitzer, underwent a demonstration at Yuma Proving Ground, Arizona, on September 15, 2005. During this demonstration, it exhibited exceptional accuracy, achieving precision better than 33 feet (10 meters) at a remarkable distance of 9 miles (15 kilometers). Testing for Excalibur continued through February 2007, with plans for operational deployment later in that year. In parallel, the US Navy contracted with Raytheon Missile Systems, the primary designer of the Army's Excalibur, for the development of the 5-inch (13-cm) mK-171 Extended-Range Guided Munition (ERGM). While achieving satisfactory ERGM performance posed challenges, delaying its operational deployment, flight demonstrations conducted at White Sands Missile Range, New Mexico, on February 16, 2005, demonstrated the ERGM's exceptional accuracy at distances exceeding 40 nautical miles. In both instances, these innovative projectiles offered increased lethality, minimized collateral damage, extended range, and significantly reduced logistical burdens for deployed forces.[158]

In early 2003, the public became aware of the integration of GPS guidance for precision airdrops. The US Army Operational Test Command employed GPS in two distinct instrument packages: one for validating the optimal rigging of heavy cargo pallets with parachutes and another for assessing new troop-parachute designs. In just a matter of months, the US military conducted operational tests of Onyx, an autonomously guided parachute system developed by Atair Aerospace. This system was designed to deliver payloads

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ranging from 75 to 2,200 pounds (34 to 998 kilograms) with a circular error probability of 246 feet (75 meters) from altitudes of up to 35,000 feet (10,668 meters) even in challenging conditions such as darkness and other extreme environments. Again, on August 9, 2004, US Marines near Camp Korean Village, Iraq, witnessed the inaugural operational use of a GPS-assisted Sherpa Parafoil cargo delivery system, a pivotal component of the Joint Precision Airdrop System (JPADS) technology demonstration program, in a combat zone. Two years later, the first joint Air Force-Army operational drop using JPADS in Southwest Asia supplied ammunition and water to troops in Afghanistan. Meanwhile, the development and testing of GPS-equipped navigation units for paratroopers advanced. In 2005, the French Military Agency (DGA) and Army Special Forces in Singapore were utilizing over 200 GPS-assisted Operational Paratroopers Navigation Systems (OPANAS) with the Onyx autonomously guided parachute system incorporating GPS navigation. Units manufactured by SSK Industries, along with NATO countries, were assessing OPANAS for high-altitude, high-opening (HAHO) jumps. These advancements ensured more precise landings for both cargo and troops in various conditions and allowed for releases from altitudes exceeding 25,000 feet (7,620 meters), enhancing the protection of aircraft and personnel from potential threats posed by cost-effective surface-to-air missiles.[159]

By 2006, one of the most widespread applications of GPS technology within the US military involved real-time tracking and coordination of various combat units. This was achieved through the utilization of the GPS-enabled Force XXI Battle Command, Brigade-and-Below (FBCB2) Satellite-based tracking system and its variant known as Blue Force Tracking (BFT). This system played a crucial role in enhancing battlefield awareness and communication. Throughout the twentieth century, American soldiers had suffered approximately a quarter-million casualties, often as a result of what was termed "friendly fire." This tragic phenomenon primarily occurred due to the challenges faced in rapidly distinguishing between friend and foe during intense conflicts. As early as the spring of 1987, engineers and scouts from the U.S. Army's 4th Infantry Division utilized two 17.5-pound (8-kilogram) GPS Manpacks during exercises in the Pinõn Canyon Training Area of southern Colorado. This allowed them to navigate through "enemy" lines, even in adverse conditions like snow, rain, fog, and darkness, to accomplish their mission. Four years later, during Operation Desert Storm, despite having only 16 satellites in the GPS constellation, GPS technology played a pivotal role in positioning and maneuvering large troop formations, facilitating precision bombing, providing artillery fire support, and supporting special operations in the relatively featureless desert terrain. Coalition forces relied heavily on more than 12,000 personal GPS receivers, each costing approximately US$3,500. These devices proved instrumental in reducing the confusion and uncertainty on the battlefield, preventing numerous casualties, and mitigating what was often referred to as the ‘fog of battle.’[160]

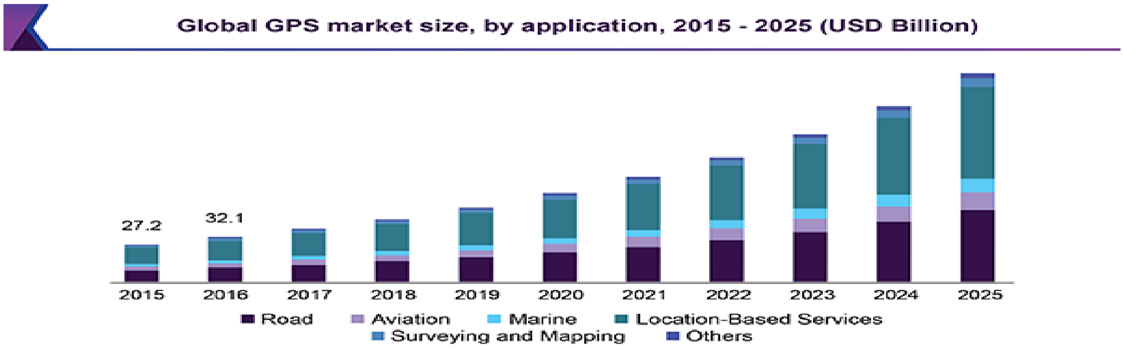
A decade after the conclusion of Desert Storm, U.S. forces engaged in military exercises in California and Florida achieved the real-time location and tracking of troops, aircraft, and various equipments using a cost-effective Range Instrumentation System (IRIS). This experimentation illustrated that readily available, low-cost, commercial off-the-shelf hardware could effectively facilitate the coordination of ground and air operations, significantly improving the safety of friendly forces. Again, by 2005, US and allied forces stationed in Kosovo, Afghanistan, and Iraq had come to rely on over 8,000 GPS-enabled FBCB2 units and an additional 2,000 FBCB2-BFT units. These systems enabled them to track their own positions, monitor the locations of neighboring friendly forces, identify enemy positions, and pinpoint the whereabouts of critical features like bridges and minefields—important information for navigating safely in hostile environments.[161] However, in 2006, Globecomm Systems secured a US$7.8 million contract to furnish NATO forces with a comparable BFT capability. The enhanced situational awareness provided by FBCB2 and its BFT variant empowered battlefield commanders to plan and execute maneuvers, both offensive and defensive, with an unprecedented level of precision.[162]

Analysis of GPS Demand and Market

In 2017, the estimated market size for GPS stood at USD 37.9 billion, with a projected Compound Annual Growth Rate (CAGR) of 18.4% during the forecast period. This anticipated growth is attributed to the increasing prevalence of smartphones and the growing number of GPS-enabled vehicles, which are expected to drive market expansion. Additionally, the rising adoption of social media in developing countries and a substantial volume of mergers and acquisitions involving component manufacturers and integrators are poised to fuel the global positioning systems (GPS) market.[163] The global GPS market is expected to experience significant growth in the near future, driven by its expanded utilization in various sectors, including military, defense, and a broad range of civilian applications. GPS devices find applications in diverse industrial sectors, contributing positively to the GPS market. Key users of GPS systems encompass transportation, construction, aerospace, and agriculture.

The integration of GPS devices enhances operational efficiency in these industries and helps reduce overall operational costs. For instance, embedded GPS units in passenger vehicles assist travelers in navigating unfamiliar routes within the transportation sector. Moreover, the increasing adoption of smartphones equipped with location-enabled services is expected to stimulate market growth in the years ahead. The emergence of high-speed mobile data technologies like 4G and 5G is further promoting the global use of GPS, thus driving the market's expansion. However, stringent regulations and licensing requirements represent some of the factors that hinder the overall market's growth. The market is categorized based on deployment into Consumer Devices, Automotive Telematics Systems, Standalone Trackers, Portable Navigation Devices, and Others. In terms of application, it is segmented into Location-Based

Services, Road, Aviation, Marine, Surveying & Mapping, and Others. GPS technology finds diverse applications across sectors such as road navigation, aviation, location-based services, marine activities, surveying, and mapping.



Source: www.grandviewresearch.com

Figure 4: Use of GPS market worldwide in USD Billions[164]

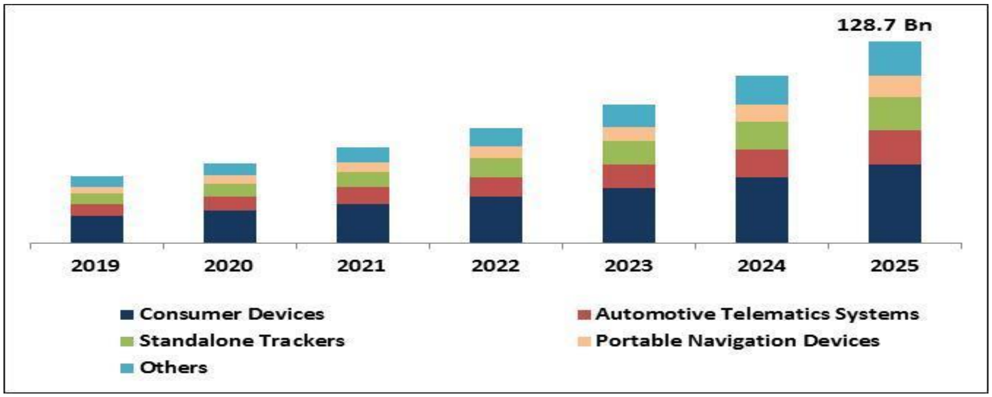


Figure 5: Use of GPS market worldwide in USD Billions[165]

Error, Effect and other Factors Analysis of GPS

Each satellite sends messages containing various information including details about the satellite's health, its orbital path, the state of its internal clock, and the overall configuration of the satellite network. To improve the accuracy of calculations, precise monitoring and measurement of existing GPS signals can be employed in additional or alternative ways. Following the discontinuation of Selective Availability by the US government, the primary source of error in GPS calculations became the unpredictable delay caused by the ionosphere. While the spacecraft transmit ionospheric model parameters, these models are inherently imperfect. Hence, GPS satellites broadcast signals on at least two frequencies, L1 and L2[166]. Ionospheric delay is a well-defined function of frequency and the total electron content (TEC) along the signal's path. Consequently, measuring the difference in arrival times between these frequencies allows for the determination of TEC and the precise ionospheric delay at each frequency. Receivers equipped with decryption keys can decode the P(Y)-code transmitted on both L1 and L2. However, these keys are restricted to the military and authorized agencies and are not available to the general public. Without decryption keys, it is still possible to utilize a codeless technique to compare the P(Y) codes on L1 and L2 to obtain much of the same error information. Nevertheless, this method is relatively slow and is currently limited to specialized surveying equipment. In the future, additional civilian codes are expected to be transmitted on the L2 and L5 frequencies, enabling all users to perform dual-frequency measurements and directly calculate ionospheric-delay errors.

Another precise monitoring method is carrier-phase enhancement (CPGPS)[167], which addresses errors arising from the non-instantaneous pulse transition of the PRN (Pseudo-Random Noise) signal. This imperfection affects the correlation operation, which matches the satellite's signal sequence with that of the receiver.[168] Assisted GNSS (A-GNSS) is a GNSS augmentation system that significantly improves the startup performance and time-to-first-fix (TTFF) of a global navigation satellite system (GNSS). A-GNSS achieves this by delivering essential data to the device via a radio network rather than relying solely on the slower satellite link. This process effectively "warms up" the receiver, expediting the process of obtaining a fix[169]. When applied to GPS, it is referred to as assisted GPS or augmented GPS. A-GPS is extensively utilized in GPS-capable cellular phones, driven in part by the US Federal Communications Commission's (FCC) 911 requirements, which mandates the availability of cell-phone location data to emergency call dispatchers.[170]

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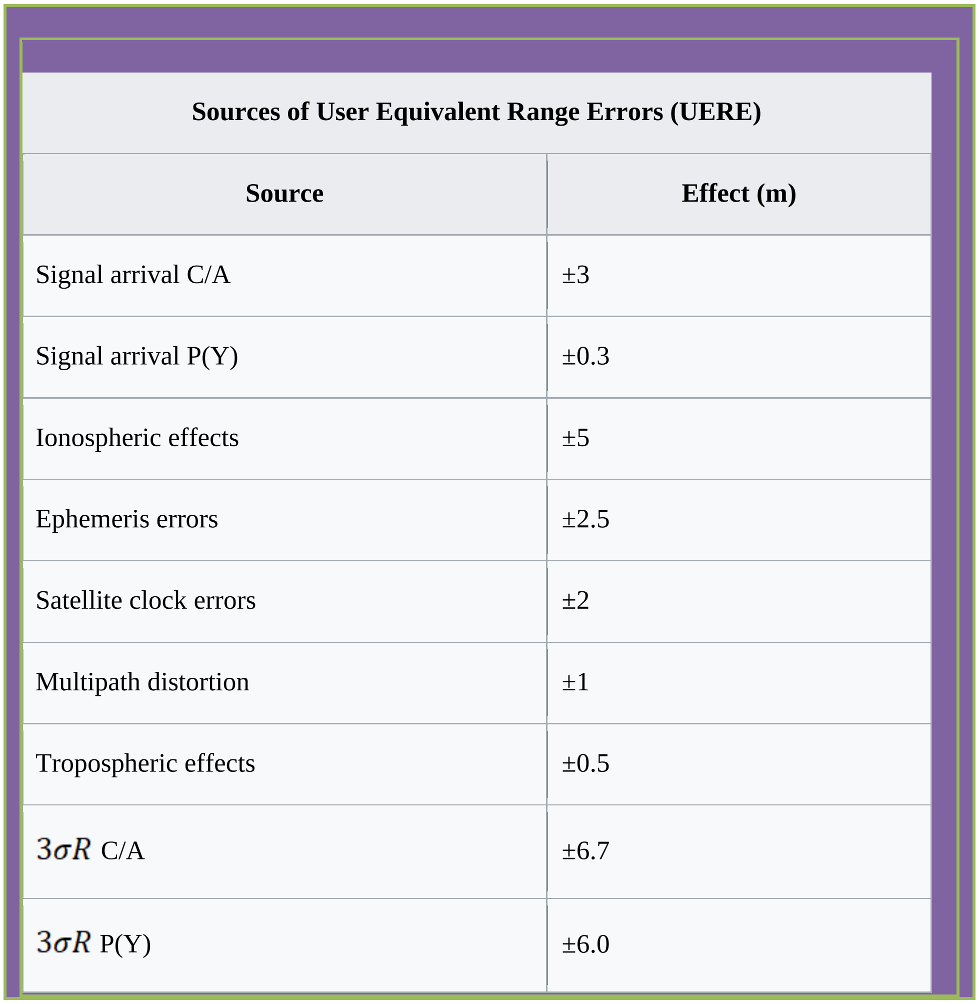
Analyzing errors in GPS is crucial for comprehending how the system operates and what level of error can be expected. While the GPS corrects for receiver clock errors and certain other factors, there remain residual errors that go uncorrected. The computation of a GPS receiver's position relies on data received from satellites, and the errors are influenced by factors such as geometric dilution of precision and other sources. The term "user equivalent range error" (UERE) pertains to the error in the distance between the receiver and a satellite. These UERE errors are typically expressed as ± values, indicating that they are unbiased or have a zero mean error. Consequently, these UERE errors are used in the calculation of standard deviations. The standard deviation of the error in receiver position, denoted as σrc, is determined by multiplying the Position Dilution Of Precision (PDOP) by σR, which represents the standard deviation of the user equivalent range errors. To compute σR, you take the square root of the sum of the squares of the individual component standard deviations.

The table below presents the user equivalent range errors (UERE) along with an estimated numerical error of approximately 1 meter (3 feet 3 inches)[171]. Additionally, the standard deviations (σR) for both the coarse/acquisition (C/A) and precise codes are provided in the table[172]. These standard deviations are calculated by taking the square root of the sum of the squares of the individual components (or RSS, which stands for root sum squares)[173]. To obtain the standard deviation of the receiver position estimate, these range errors must be adjusted by the appropriate dilution of precision terms and then combined using the RSS method[174].Electronic errors are one among several factors that can degrade accuracy, as outlined in the table above. Collectively, autonomous civilian GPS horizontal position fixes are typically accurate to approximately 15 meters (50 feet). These effects also impact the accuracy of the more precise P(Y) code. However, technological advancements mean that in current times, civilian GPS fixes with an unobstructed view of the sky are generally accurate to around 5 meters (16 feet) horizontally on average.



Sources of User Equivalent Range Errors (UERE)

Source	**Effect (m)**
Signal arrival C/A	±3
Signal arrival P(Y)	±0.3
Ionospheric effects	±5
Ephemeris errors	±2.5
Satellite clock errors	±2
Multipath distortion	±1
Tropospheric effects	±0.5
$3\sigma R$ C/A	±6.7
$3\sigma R$ P(Y)	±6.0

Table 1: The user equivalent range errors (UERE) for GPS

The calculation of a GPS receiver's position relies on several key factors, including the current time, the satellite's position, and the measured delay of the received signal. The primary determinant of position accuracy is the satellite's position and the delay in the signal. To measure this delay, the receiver compares the received signal's bit sequence with an internally generated version. Using modern electronics, signal offset can be measured with precision, typically within about one percent of a bit pulse width, equivalent to approximately 10 nanoseconds for the C/A code. Given that GPS signals travel at the speed of light, this level of precision results in an error of around 3 meters. This aspect of position accuracy can be enhanced by a factor of 10 when using the higher-chiprate P(Y) signal. Assuming the same 1% accuracy of bit pulse width measurement, the high-frequency P(Y) signal yields a positional accuracy of approximately 30 centimeters. It's important to note that various other factors, errors, and effects can influence the overall accuracy of GPS positioning, and these are described further below.

Atmospheric effects. The accuracy of GPS location is significantly affected by atmospheric effects, which affect the speed of signals as they travel through the Earth's atmosphere, particularly the ionosphere. Establishing and correcting these errors is a major challenge. These effects are less pronounced when satellites are directly above us, but become more significant when they are closer to the horizon due to the longer path through the atmosphere.[175] Once the receiver's approximate location is known, a mathematical model can be used to estimate and compensate for these errors. Ionospheric delay of a microwave signal depends on its frequency. It arises from ionized atmosphere.[176] This phenomenon is known as dispersion and can be calculated from measurements of delays for two or more frequency bands, allowing delays at other frequencies to be estimated.[177] In military and civilian survey-grade receivers, different delays at different frequencies can be used to calculate atmospheric dispersion, and more precise corrections can be applied. This can be achieved by following the carrier signal rather than the modulated code on L2, without decoding the P(Y)[178]. In order to facilitate this on low-cost receivers, a civilian code signal on the L2, designated as L2C, has been added to the Block IIIR-M satellites launched in 2005. This signal allows for direct comparison of the signals of the two satellites, using the coded signal rather than the carrier wave. Ionospheric effects typically vary over time and can be averaged. These effects can be calculated for any specific geographical area by comparing the GPS measured position to a well-known surveyed location. The correction can also be applied to other receivers located in the same general area. Several systems transmit this information via radio or other links, enabling L1-receiving receivers to make ionosphere corrections. Ionospheric data is transmitted via satellite in satellite-based subsystems (SBAS) such as WAAS (North America, Hawaii, Europe and Asia) and MSAS (Japan) which transmit it on GPS frequency using a unique pseudo-random noise (PRN) sequence. Humidity causes a variable delay which results in errors similar to those found in the troposphere. This effect is distinct from ionospheric effects in that it is more localized, changes more rapidly, and is not frequency-dependent, making it difficult to accurately measure and compensate for humidity errors.[179] The Atmospheric pressure can also change the signals reception delay, due to the dry gases present at the troposphere (78% N_2, 21% O_2, 0.9% Ar, 0.04% CO_2). Its effect varies with local temperature and atmospheric pressure in quite a predictable manner using the laws of the ideal gases.[180]

Multipath effects. Multipath issues, which are caused by radio signals reflecting off of surrounding terrain, can lead to measurement errors that vary depending on the wavelength of the GPS signal.[181] These delayed signals cause measurement errors that are different for each type of GPS signal due to its dependency on the wavelength.[182] A variety of techniques, most notably narrow correlator spacing, have been developed to mitigate multipath errors. For long delay multipath, the receiver itself can recognize the wayward signal and discard it. To address shorter delay multipath from the signal reflecting off the ground, specialized antennas like, choke ring antenna may be used to reduce the signal power as received by the antenna.[183] Short delay reflections are more challenging to filter out due to the fact that they are impinging on the actual signal, leading to results that are nearly indistinguishable from standard atmosphere delay variations. Stable solutions are significantly less likely to be affected by multiplath effects when the vehicle is stationary. False solutions resulting from reflected signals do not converge quickly when the GPS antenna is moving. Only direct signals offer stable solutions.

Ephemeris and clock errors. The ephemeris data are transmitted at a rate of every 30 seconds, however, the data itself may be as old as two hours old. The influence of solar radiation pressure on GPS accuracy is indirect, as it affects ephemeris errors..[184] If a fast time to first fix (TTFF) is needed, it is possible to upload a valid ephemeris to a receiver, and in addition to setting the time, a position fix can be obtained in under ten seconds.[185] It is feasible to put such ephemeris data on the web so it can be loaded into mobile GPS devices.[186] The satellites' atomic clocks experience noise and clock drift errors.[187]The accuracy of the clocks is estimated from observations, however, these estimates may not accurately reflect the current state of the clocks. Although these errors are typically very small, they can lead to considerable inaccuracy, varying from a few metres to a few tens of feet..[188] For very precise positioning like geodesy, these effects can be eliminated by differential GPS (DGPS). Interestingly, any DGPS supplement and enhance the positional data available from global navigation satellite systems (GNSSs). A DGPS for GPS can increase accuracy by about a thousand-fold, from approximately 15 m to 1–3 cm.[189] Two or more receivers are used simultaneously at multiple survey points. During the 1990s, due to the relatively high cost of receivers, certain methods of QDG were developed, where only one receiver was used, but re-location of measuring points was re-used. At the Technical University of Vienna, the method was christened qGPS. Post processing software was also developed.

Selective Availability. Prior to its introduction, Global Positioning System (GPS) had a feature known as Selective Accessibility (SA). SA enabled the addition of deliberate, time varying errors to publicly available navigation signals, up to a maximum of 100 meters (328 feet). This was intended to prevent an enemy from utilizing civilian GPS receivers for the purpose of precision weapon guidance. In reality, SA errors are pseudorandom, which is a cryptographic algorithm generated from a secret seed key that can only be accessed by authorized users (the United States military, its allies, and a select few other users, primarily government) with a

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specialized military GPS receiver.[190] It is not sufficient to simply possess the receiver; it still requires the strictly regulated daily key. Prior to the shutdown of the receiver on 2 May 2000, the typical SA errors were approximately 50 meters (164 feet) horizontally and approximately 100 meters (160 feet) vertically.[191] . This is due to the fact that SA affects all GPS receivers in a given geographical area approximately in the same manner. A fixed station with a precisely identified position can measure and transmit the SA error values to local GPS receivers in order to enable them to rectify their position fixes, a process known as Differential GPS, or DGPS.[192] DGPS also corrects for several other important sources of GPS errors, particularly ionospheric delay, so it continues to be widely used even though SA has been turned off. The ineffectiveness of SA in the face of widely available DGPS was a common argument for turning off SA, and this was finally done by order of President Clinton in 2000.[193] DGPS services are widely available from both commercial and government sources. The latter include WAAS and the US Coast Guard's network of LF marine navigation beacons.[194] The precision of the corrections is contingent upon the distance between user and DGPS receiver, and as the distance increases the errors at both sites will not be correlated, thus leading to less accurate differential corrections. For example, during the 1990–91 Gulf War, due to a lack of available military GPS units, many military personnel and their families purchased readily accessible civilian units.[195] Selective Availability had a significant impact on the US Army's ability to utilize these GPS systems on the battlefield, necessitating the decision to permanently disable them during the course of the conflict. In the mid-1990s, the Federal Aviation Administration (FAA) began to exert pressure on the military to permanently disable SA, which would have resulted in a significant reduction in FAA maintenance costs for its own radio navigation system, saving millions of dollars annually.[196] The amount of error added was 'set to zero'at midnight on May 1, 2000 following an announcement by US President Bill Clinton, allowing users access to the error-free L1 signal.[197] In accordance with the Directive, the SA induced error was modified to no longer add any error to the C/A code of the public signals. As mandated by the Clinton Executive Order, SA had to be set at zero by the year 2006; this was achieved in 2000 when the US military developed a novel system that allows for the denial of GPS (as well as other navigation) to enemy forces in a designated area of conflict, without affecting the international community or the US military's own systems. On September 19, 2007, the United States Department of Defense declared that future GPS[198] will not be capable of implementing SA, eventually making the policy permanent.[199]

Dilution of Precision. Observational error can be divided into two components: accuracy and precision. Accuracy is the degree to which a set of observations (or readings) are close to their actual values, while precision is the degree of closeness between measurements.[200] In other words, precision is a description of random errors, a measure of statistical variability.[201] Dilution of precision (DOP), or geometric dilution of precision (GDOP), is a term used in satellite navigation and geomatics engineering to specify the error propagation as a mathematical effect of navigation satellite geometry on positional measurement precision.[202]The term "Dilution of Precision (DOP)" is derived from the users of the LORAN-C navigational system. Geometrically, DOP refers to the effect of measurement errors on the final state estimate. This term can be used to describe other location systems which utilize multiple geographically distributed sites. Dilution of Precision can also be used in the context of Electronic Countermeasures (ECM).[203] when computing the location of enemy emitters by radar jammers or by radio communications devices.[204] Using interferometry technique can provide certain geometric layout where there are degrees of freedom that cannot be accounted for due to inadequate configurations. Interferometry is a technique which uses the interference of superimposed waves to extract information.[205] Interferometry is a scientific investigation technique that typically utilizes electromagnetic waves. It is widely used in the fields of Astronomy, Fiber Optics, Engineering Metrology, Optical Metrology, Oceanography, Seismology, Spectroscopy (including its applications to Chemistry), Quantum Mechanics, Nuclear and Particle Physics, Plasma Physics, Biomolecular Interactions, Surface Profiling, Microfluidics, Mechanical Stress/Strain Measurement, Velocimetry, Optometry, and Making Holograms.[206]Geometric Dilution of Precision (GDOP), a measure of the impact of satellite geometry on position error, is commonly interpreted as a ratio of position inaccuracy to range inaccuracy. For example, imagine a square pyramid composed of lines connecting four satellites, with the receiver positioned at the apex. The higher the volume of this pyramid, the lower the GDOP value. Conversely, the lower the volume, the lower the value of the GDOP. Circular Error Probability (CEP) is another measure of satellite geometry in military science.[207] or circular error probability[208] or circle of equal probability[209] is a measure of a weapon system's precision.[210] It is defined as the radius of a circle, centered on the mean, whose perimeter is expected to enclose the landing points of 50% of the rounds; said otherwise, it is the median error radius.[211] That is, if a given munitions design has a CEP of 100 m, when 100 munitions are targeted at the same point, 50 will fall within a circle with a radius of 100 m around their average impact point. Again, the distance between the target point and the average impact point is referred to as bias.[212] The concept of distance root mean square (DRMS), the square root of average squared distance error (SQD), and R95, the radius of the ring in which 95% of values would fall, are related concepts. Additionally, the concept of CEP is used to measure the precision of a position acquired by a navigational system, such as a GPS system or an older system such as a LORAN or Loran-C.

Anti-spoofing. Another restriction on GPS remains in place: antispoofing. This means that the P-code is encrypted, preventing it from being imitated by a transmitter transmitting false data. The P-code has never been used by civilian receivers, and the precision achievable with the publicly available C/A code has been significantly higher than initially anticipated, particularly with DGPS, to the extent that the anti-poof policy has had a relatively minor impact on most civilian users.[213] The primary benefit of de-spoofing anti-spoofs would be for surveyors and certain researchers who require extremely precise positioning for experiments such as monitoring tectonic plate movement.[214]

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Relativity. The theory of relativity introduces several effects that need to be taken into account when dealing with precise time measurements.[215]In accordance with special relativity, the passage of time is affected differently for objects that are moving relative to each other. This phenomenon is referred to as "kinetic time dilation": in an inertial frame of reference, the more quickly an object moves relative to the frame's clocks, the less time it appears to have elapsed.[216] General relativity takes into account also the effects that gravity has on the passage of time. In the context of GPS the most prominent correction introduced by general relativity is gravitational time dilation.[217] It means that, the clocks located deeper in the gravitational potential well or closer to the attracting body appear to tick slower. Again, special relativity predicts that as the velocity of an object increases (in a given frame), its time slows down (as measured in that frame). For instance, the frequency of the atomic clocks moving at GPS orbital speeds will tick more slowly than stationary clocks by a factor of 10^{-10} where the orbital velocity is v = 4 km/s and c = the speed of light. The result is an error of about -7.2 μs/day in the satellite.[218] The special relativistic effect is due to the constant movement of GPS clocks relative to the Earth-centered, non-rotating approximately inertial reference frame.[219] In short, the clocks on the satellites are slowed down by the velocity of the satellite. This time dilation effect has been measured and verified using the GPS. However, special relativity allows the comparison of clocks only in a flat spacetime, which neglects gravitational effects on the passage of time.[220]The general theory of general relativity states that the curvature of spacetime is caused by the presence of gravitational bodies (e.g. the Earth), making the comparison of clocks less straightforward than in special relativity. Nevertheless, most of the difference can be explained by the introduction of gravitationally-induced time dilation, which is the acceleration of time in the vicinity of gravitating bodies.[221]In the case of the Global Positioning System (GPS), the receivers are located at a greater distance from the Earth than from the satellites, resulting in a gravitational frequency shift of 5x10−10 for clocks at the satellite's altitude. This frequency shift is quantifiable. Initially, there was some uncertainty as to whether GPS would be affected by General Relativity effects, however, the results of Hafele and Keating's experiment demonstrated that GPS is not affected by these effects.[222]

Combined kinetic and gravitational time dilations. Combined, these sources of time dilation cause the clocks on the satellites to gain 38.6 microseconds per day relative to the clocks on the ground. This is a difference of 4.465 parts in 10^{10}.[223] Without correction, errors of roughly 11.4 km/day would accumulate in the position.[224] This pseudorange error will be rectified during the navigation equation solving process. Additionally, satellite orbits are elliptical, not perfectly circular, which leads to variations in the temporal dilation and frequency shift effects. As a result of the eccentricity effect, the clock rate differential between GPS satellites and a receiver increases or decreases depending on the satellite's altitude. To rectify this, each satellite's frequency standard is assigned a rate offset before launch, resulting in a slightly lower frequency than the desired one on Earth; for example, the standard frequency is set to 10.2299999943 MHz, rather than 10.2399943 MHz..[225] Since the atomic clocks on board the GPS satellites are precisely tuned, it makes the system a practical engineering application of the scientific theory of relativity in a real-world environment.[226] Placing atomic clocks on artificial satellites to test Einstein's general theory was proposed by FriedwardtWinterberg in 1955.[227]The combination of Special and General effects make the net time dilation at the equator equal to that of the poles, which in turn are at rest relative to the center. Hence we use the center as a reference point to represent the entire surface.[228] Once again, in order to neutralize both kinetic and gravitationally induced time dilation, the clock shall be slowed from the specified frequency (10.23 MHz) to the specified frequency (10.2299999943 MHz).

Sagnac distortion. GPS observation processing must also compensate for the Sagnac effect.[229] The GPS time scale is defined in an inertial system but observations are processed in an Earth-centered, Earth-fixed (co-rotating) system.[230]A coordinate transformation is then employed to transition from inertial to ECEF. The resultant signal run time correction displays opposite algebras for satellites in the eastern and western hemispheres. Neglecting this effect will result in an east-west error of several hundred nanoseconds or tens of metres in position.[231]

Natural sources of interference. Due to the fact that GPS signals at ground-based receivers are typically low-frequency, the desensitization of the receiver to natural radio signals, or the scattering of GPS signals, may render the acquisition and monitoring of satellite signals impracticable or impossible.[232] Space weather degrades GPS operation in two ways, direct interference by solar radio burst noise in the same frequency band[233] or by scattering of the GPS radio signal in ionospheric irregularities referred to as scintillation.[234] Both forms of degradation follow the 11 year solar cycle and are a maximum at sunspot maximum although they can occur at any time.[235] Solar radio bursts are associated with solar flares and coronal mass ejections (CMEs) and their impact can affect reception over the half of the Earth facing the sun.[236] Scintillation occurs most frequently at tropical latitudes where it is a night time phenomenon.[237] It occurs less frequently at high latitudes or mid-latitudes where magnetic storms can lead to scintillation.[238] In addition to producing scintillation, magnetic storms can produce strong ionospheric gradients that degrade the accuracy of SBAS systems.[239]

Artificial sources of interference. In automotive GPS receivers, metallic features in windshields,[240] such as defrosters, or car window tinting films can act as a Faraday cage, degrading reception just inside the car.[241] Man-made EMI (electromagnetic interference) can also disrupt or jam GPS signals. In one well-documented case it was impossible to receive GPS signals in the entire harbor of Moss Landing, California due to unintentional jamming[242] caused by malfunctioning TV antenna preamplifiers.[243] It is possible for GPS receivers to be jammed intentionally. Generally, more powerful signals can be disruptive when they are in radio range or within the receiver's field of view. In 2002, Phrack published an in-depth article on the construction of a GPS L1C/A short-range jammer.[244] It

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has been reported by the United States government that GPS jammers were occasionally employed in the War in Afghanistan. Additionally, six GPS jammers were destroyed by the United States military in the course of the Iraq War, one of which was destroyed by a GPS-guided explosive, demonstrating the inadequacy of the jammers employed in that situation.[245] A GPS jammer is relatively easy to detect and locate, making it an attractive target for anti-radiation missiles.[246] The UK Ministry of Defence tested a jamming system in the UK's West Country on 7 and 8 June 2007. Some countries allow the use of GPS repeaters to allow the reception of GPS signals indoors and in obscured locations; while in other countries these are prohibited as the retransmitted signals can cause multi-path interference to other GPS receivers that receive data from both GPS satellites and the repeater. In the UK Ofcom now permits the use of GPS/GNSS Repeaters under a 'light licensing' regime.[247] Again, due to the potential for both natural and man-made noise, numerous techniques continue to be developed to deal with the interference. The first is to not rely on GPS as a sole source. According to John Ruley, IFR pilots should have a fallback plan in case of a GPS malfunction.[248] Receiver Autonomous Integrity Monitoring (RAIM) is a feature included in some receivers,[249] designed to provide a warning to the user if jamming or another problem is detected. The U.S. military has also deployed since 2004 their Selective Availability/Anti-Spoofing Module (SAASM)[250] in the Defense Advanced GPS Receiver (DAGR).[251] In demonstration videos the DAGR was shown to detect jamming and maintain its lock on the encrypted GPS signals during interference which caused civilian receivers to lose lock.[252]

Analysis of Present and Future of GPS

GPS is the premium standard for precise positioning, navigation, and timing (PNT), and it has an impact on the lives of almost six billion people worldwide.[253] The economy United States is solely dependent on free government-provided service over 900 million GPS devices supports automobile navigation systems, general aviation, financial transactions, the electrical grid, precision agriculture, surveying, and building construction. The GPS organization must maintain consistency and dependability while keeping up with changing technologies without causing disruption to the end user.[254] The US Space Force's space development, procurement, launch, and logistics field command, Space Systems Command (SSC) at Los Angeles Air Force Base in El Segundo, California, is in charge of sustaining and modernizing the GPS business.[255] The enterprise is divided into three sections: the space section, the control section, and the user section.

Space Segment. There are 37 GPS satellites in orbit, with at least 31 of them still operational. The constellation requires 24 functioning satellites for global coverage, and a receiver must receive broadcasts from four of them to identify its position in three dimensions. The constellation continues to operate brilliantly with average 45 cm accuracy year after year. GPS modernization in space focuses on GPS III and GPS IIIF satellite development, with important milestones in 2022.**[256]**Following the successful launch of Space Vehicle 5 (SV05) on June 17, 2021, and has made it useable for GPS III on May 25, 2022. The significance of SV05 is its improved civilian L2 (L2C) signal's complete operating capacity. Because it has access to two frequencies, L2C enhances service speed for commercial users, improves accuracy when paired with legacy civil GPS signals (L1 C/A), and is less vulnerable to ionospheric interference.**[257]**SV05 is the 24th satellite that provides global M-code coverage. M-code is intended to provide military receivers with higher jamming resistance, increased accuracy, a more secure and adaptable encryption architecture, and the capacity to detect and reject fake signals. SV06 was successfully launched into orbit from Cape Canaveral Space Force Station in Florida on January 18, 2023, aboard a SpaceX Falcon 9 Block 5 rocket.**[258]**The launch of SV06 is a significant step toward the greater goal of upgrading the GPS constellation.In addition, the 10th and final satellite in the GPS III fleet has completed manufacture and is scheduled to launch in 2026. GPS III Space Vehicles 7-10 are now in storage and ready for launch. The development of the next generation of GPS satellites continues. The contract award for GPS III Follow-On (GPS IIIF) satellites in October 2022 will include extra capabilities.**[259]**The GPS IIIF satellites will provide a new Regional Military Protection (RMP) capability with up to 60 times greater anti-jamming measures, in addition to new civil signals designed to improve SAR efficacy and aviation safety, a laser retro-reflector array for precise ranging, and a fully digital navigation payload. A new port on the Lockheed Martin LM2100 Combat Bus provides tremendous flexibility, allowing for the rapid integration of payloads in response to emerging space threats.

Control Segment. The present GPS Operational Control System (OCS) will be replaced by the Next Generation Operational Control System (OCX), according to the most recent US Department of Defense cybersecurity requirements and procedures. The revised system features a modernized and extended network of monitor stations, stronger anti-jam capabilities, and greater operational capability to regulate modernized military communications.**[260]**According to Ellen Hall of Spirent Federal Systems, "the OCX system is part of a massive modernization effort to improve the ground control segment of the current GPS." This improvement alone improves accuracy, but when combined with upgraded satellites, the next generation OCX will expand and improve GPS coverage and security. In terms of coverage, the Next Generation OCX will be able to fly twice as many satellites, including legacy and GPS IIIF satellites. In terms of security, the updated receivers include anti-jam capabilities as well as information assurance measures.**[261]**OCX completed its fourth and last legacy ground antenna element (LGAE) installation on Kwajalein Island, Republic of the Marshall Islands, in March 2022. Hewlett Packard (HP) Formal Qualification Test (FQT) is being performed on OCX Blocks 1 and 2. This event will validate several of the previously validated mission software functions of the system. In addition, the event will highlight system maturity and readiness for system acceptance, as well as operator training and specific developmental testing milestones with both GPS space and

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user segments. OCX 3F, the next-generation control system, will alter OCX Blocks 1 and 2 to take advantage of the expanded capabilities of GPS IIIF satellites. The Milestone Decision Authority (MDA) approved Milestone B and the Acquisition Program Baseline (APB) for OCX 3F, allowing it to enter the Engineering and Manufacturing Development (EMD) phase in May. Following the completion of the program's first Integration Readiness Review (IRR), the OCX 3F program deployed 3F mission software for the first time into OCX's Near Operations Environment (NOE) in November. Prior to releasing software to operational users, the IRR event ensures that the software meets integrity standards and is approved for integration and testing on the NOE. The OCX 3F is expected to be operational in 2027.

User Equipment Segment. Only a few types of GPS user equipment have the technology to use the M-code signal. The usage of these signals is required to maintain a competitive advantage over the opponent; the GPS Enterprise is focused on creating Modernized GPS User Equipment (MGUE) capable of accessing these signals. The MGUE initiative is a combined service effort to update M-code-capable military GPS receivers. The program is divided into two parts (Inc 1 and Inc 2). Both are intended to provide secure PNT performance, enable navigation warfare operations, improve anti-jam, anti-spoofing, and anti-tampering, and enable Blue Force Electronic Attack.[262] L3Harris delivered its final Build 7 ground card to the government on Nov. 16, 2021, as part of the MGUE Inc 1 package, and completed regression testing on that kit in February 2022. Delta Security Approval and Certification were accomplished on April 13, 2022 and April 29, 2022, respectively. The L3H Ground-Based GPS Receiver Applications Module (GB-GRAM-M) card has completed development and is now available for service procurement, providing geo-location and accurate positioning capabilities for space-constrained applications while also delivering increased security and anti-jam capabilities. On September 9, 2022, MGUE Inc 1 completed certification testing for the aviation and maritime cards, using upgraded software releases.[263] This build advances the program to 98% verification of requirements, allowing B-2 Bombers and Guided Missile Destroyers (DDG) to continue progress toward operational testing. With the completion of this commitment, stakeholders and warfighters will have made substantial progress toward operational testing.[264]

In the summer of 2022, MGUE Inc 2 held Preliminary Design Reviews for the Miniature Serial Interface (MSI), bringing the project one step closer to completion of the EMD phase. The government will consider each event complete once all closure and action items for the evaluations have been completed. This summer's Critical Design Review (CDR) will assess the system design and capacity to meet system performance objectives. MGUE Inc 2 continues to carry out the second competitive goal under Phase I for the Joint Modernized Handheld component; the endeavor is nearing completion of the handheld prototype, which will allow for a smoother transfer to operations.[265] The SSC's mandate is critical to preserving our modern way of life.[266] GPS technology is being developed by space specialists who are dedicated to providing new capabilities to the warfighter, the civil sector, and the world. We are entering an interconnected world. We're already on our way.[267]SSC is the field command of the United States Space Force in charge of obtaining and deploying the capabilities required by warfighters to protect our nation's strategic edge in and from space. It handles a $11 billion budget for the US Department of Defense and collaborates with joint forces, business, government agencies, academic institutions, and affiliated groups to keep up with developing threats.[268]

It is often overlooked that GPS is still a military device manufactured at a cost of US$ 12 billion by the Department of Defense and intended largely for military use. This fact has sparked one of the few disputes concerning the system's remarkable performance. GPS, like any new technology, carries risks, and it might be exploited to aid traffickers, terrorists, or enemy forces. Only after being pressed by the corporations that produced the equipment and saw the large potential market for it did the Pentagon make the GPS system accessible for commercial use. However, as a compromise, the Pentagon implemented a strategy known as selective availability, under which the most accurate signals broadcast by GPS satellites would be tightly reserved for military and other authorized users. GPS satellites currently emit two signals: one for civilians that is accurate to within 100 feet and another for the military that is accurate to within 60 feet. The Pentagon has also reserved 24 Navstar satellites, each the size of a big automobile and weighing approximately 1,900 pounds, which orbit the Earth at 11,000 miles altitude. The satellite system was finished in 1993, 20 years after it was first envisioned in the Pentagon with Lockheed Martin Astro Space. It was manufactured by Rockwell International and operated by the US Air Force.[269] The White House said in March 1996 that everyone would have access to the maximum level of GPS accuracy, and that the practice of weakening civil GPS signals would be phased out within a decade. The White House also restated the federal government's commitment to offering GPS services on a global, free-of-charge basis for peaceful civic, commercial, and scientific purposes.[270] GPS's potential appears to be nearly limitless; technical dreams abound. The method creates a new, unique, and instantly accessible address for every square yard on the planet's surface, as well as a new international standard for location and distance. Our locations, at least to computers around the world, may be characterized by longitude and latitude rather than a street address, a city, and a state. The search for a local restaurant or the nearest gas station in any city, town, or suburb will be completed in an instant thanks to the GPS position of services stored with phone numbers in computerized yellow pages.[271] With GPS, the world has been gifted a technology with limitless potential, produced in the laboratories of scientists driven by their own curiosity to investigate the nature of the universe and our world, and built on the fruits of publicly funded basic research.

By the time GPS satellite signals reach the Earth's surface, they are quite feeble. The signals travel through line of sight, therefore they can pass through clouds, glass, and plastic but not most solid objects, including buildings and mountains. Modern receivers, on the

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other hand, are more sensitive and can usually track through houses. At the moment, GPS satellites are being launched with an additional frequency known as L5. In comparison to the original L1 signal, this upgraded signal has more strength and superior tracking characteristics. L5 is now used in recent Garmin GPS receivers to increase accuracy and dependability. This multi-band approach (L1 and L5) improves performance beneath trees and in urban canyons.[272] A GPS signal carries three kinds of information:

- **A pseudorandom code** is an identification code that indicates which satellite is providing data. On your device's satellite page, you can see which satellites are sending you signals.
- **Ephemeris data** is required to establish a satellite's position and provides critical information about a satellite's health, current date, and time.
- **Almanac data** tells the GPS receiver where each GPS satellite should be at any given time over a period of months and displays orbital information for that satellite and every other satellite in the system.

GPS units do not often work underwater or underground. High-sensitivity receivers, on the other hand, can monitor some signals while within buildings or under tree cover. The L5 signal increases the receiver's capacity to distinguish between reflections and line of sight.[273] The following factors can have an impact on GPS signal and accuracy:

- **Ionosphere and troposphere delays:** Satellite transmissions travel slowly through the atmosphere. To correct for this type of mistake, the GPS system has a built-in model.

- **Signal multipath:** The GPS signal may reflect off things such as towering buildings or big rock surfaces before reaching the receiver, increasing the signal's travel time and causing mistakes.
- **Receiver clock errors:** Because atomic clocks aboard GPS satellites are more accurate, a receiver's built-in clock may have minor timing mistakes.
- **Orbital errors:** The reported location of the satellite may be inaccurate.
- **Number of satellites visible:** The more satellites that a GPS receiver can link to, the more accurate it will be. Position mistakes or no position signal may occur when a signal is obstructed.
- **Satellite geometry/shading:** Satellite transmissions are more effective when they are spread out rather than in a line or close collection of satellites.
- **Selective Availability (SA):** To prevent enemies from using highly accurate GPS signals, the USDOD once applied SA to satellites, making signals less accurate. In May 2000, the government turned off SA, which enhanced the accuracy of civilian GPS receivers.

Existing Different GNSS in the World

Other systems identical to GPS exist around the world, and they are all designated as global navigation satellite systems (GNSS). The term "GNSS" refers to all satellite navigation systems. The majority of Garmin receivers track GPS, GLONASS, and Galileo, with certain regional variations tracking BeiDou and QZSS as well. Because they track and use many satellite constellations, these are sometimes referred to as multi-constellation receivers. When we follow additional satellites, we can expect a more reliable answer. With newer Garmin systems, we could be tracking roughly 20 or 30 satellites. Figure 6 shows a comparison of GPS, GLONASS, Galileo, BeiDou-2, and COMPASS (medium Earth orbit satellites) orbits with the International Space Station, Hubble Space Telescope, geostationary and graveyard orbits, and the nominal size of the Earth. The three-dimensional aspect of orbits has been simplified for this diagram. For example, the illustrated view of the Earth is looking down to the North Pole, giving the orbit representations the appearance of being equatorial. While this is correct for geostationary orbits, the other orbits listed have substantial inclinations. Iridium orbits have an inclination of 86.4°, which is approximately perpendicular to the diagrammed plane. Looking down from this zenith, a polar orbit with a 90° inclination would seem as a straight line. At the moment, we are aware of four worldwide navigation satellite systems, as previously described. There are also a number of regional satellite systems. These worldwide navigation satellite systems are: NAVSTAR (or GPS) for the United States, GLONASS for Russia, Galillio for the European Union, and BeiDou - 2 for China. A quick description is provided below.

NAVSTAR (GPS). The Global Positioning System (GPS) of the United States is made up of up to 32 MEO satellites in six different orbital planes. As older satellites are retired and replaced, the exact number of satellites varies.[274] GPS has been in operation since 1978 and has been available globally since 1994. It is the world's most widely used satellite navigation system. [275] The above paragraphs provide a detailed description of GPS. This paper mostly discusses GPS's history, applications, and future prospects.[276] Its functioning principle and other details are shown in the reference videos.[277,278]

GLONASS. The former Soviet, and now Russian, Global'naya Navigatsionnaya Sputnikovaya Sistema, or GLONASS), is a space-based satellite navigation system that provides civilian radio-navigation satellite service and is also utilized by the Russian Aerospace Defence Forces. [279] GLONASS has provided complete global coverage since 1995 and now has 24 operating satellites.[280] It's working principal and other information has been shown in the ref videos.[281,282]

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Galillio. In March 2002, the European Union and the European Space Agency reached an agreement to develop their own alternative to GPS, known as the Galileo positioning system.[283] Galileo achieved global Early Operational Capability (EOC) on December 15, 2016. Originally budgeted at approximately €10 billion,[284] the this system was initially slated to be fully operational by 2010.[286] The original year to become operational was 2014.[287] The inaugural experimental satellite was successfully launched on December 28, 2005.[288] Galileo is anticipated to be fully compatible with the modernized GPS system.[289] The receivers will be able to combine the signals from both Galileo and GPS satellites to greatly increase the accuracy.[290] The complete Galileo constellation comprises 24 active satellites, the most recent of which was launched in December 2021.[291] The primary modulation utilized in the Galileo Open Service signal is the Composite Binary Offset Carrier (CBOC) modulation.[292] Further details and operational principles can be found in the reference videos.[293,294]

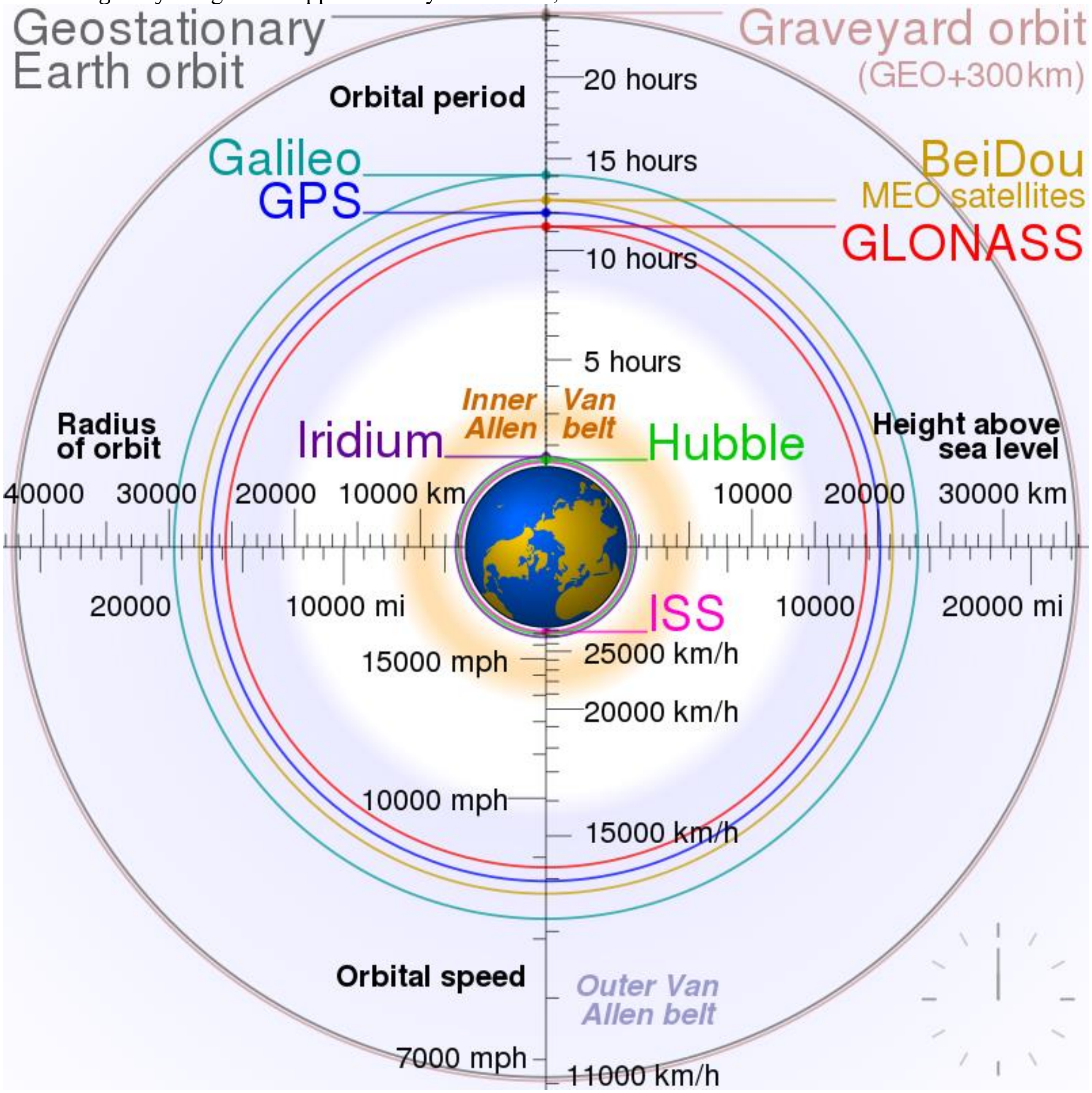

Figure 6: Comparison of navigation satellite in orbits[285]

BeiDou -2 and 3. BeiDou commenced with the now-retired Beidou-1, a regional geostationary network in the Asia-Pacific region. The second iteration, BeiDou-2, achieved operational status in China by December 2011.[295] The proposed BeiDou-3 system is designed to encompass 0 MEO satellites and five geostationary satellites (IGSOA regional version comprising 16 satellites (covering Asia and the Pacific) was finalized by December 2012, with global coverage achieved by December 2018.[296] Global service was completed by December 2018.[297] On June 23, 2020, the BDS-3 constellation deployment was successfully completed with the launch of the last satellite from the Xichang Satellite Launch Center.[298] China Satellite Communications Co., Ltd., also known as China Satcom, is a Chinese aerospace firm offering satellite services. China Satellite Communications Co., Ltd., also known as China Satcom, is a

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Chinese aerospace firm offering satellite services.[299] It was formerly a subsidiary of China Aerospace Science and Technology Corporation (CASC), operated satellites under the brand Apstar. Prior to its re-incorporation as a limited company, the entity was known as China Satellite Communications Corporation. Further details and operational insights can be found in the reference videos.[300,301]

The BeiDou Navigation Satellite System represents China's satellite navigation system, comprising two distinct satellite constellations.[302] The initial BeiDou system, officially designated as the BeiDou Satellite Navigation Experimental System[303] and commonly referred to as BeiDou-1, comprised three satellites. It commenced operations in 2000, offering limited coverage and navigation services primarily to users in China and neighboring regions.[304] BeiDou-1 was retired by the close of 2012.[305] The system's second iteration, officially named the BeiDou Navigation Satellite System (BDS) and also known as COMPASS or BeiDou-2, achieved operational status in China in December 2011, featuring a partial constellation of 10 satellites in orbit.[306] From December 2012 onward, it began providing services to customers in the Asia-Pacific region[307]. Within this region, BeiDou exhibited superior accuracy compared to GPS.[308] In 2015, China initiated the third-generation BeiDou system, BeiDou-3, designed for global coverage. The inaugural BDS-3 satellite was launched on March 30, 2015[309], and on December 27, 2018, the BeiDou Navigation Satellite System commenced offering global services.[310] The 35th and the final satellite of BDS-3 was launched into orbit on 23 June 2020.[311] It was projected in 2016 that BeiDou-3 would achieve millimeter-level accuracy through post-processing.[312] On June 23, 2020, the most recent BeiDou satellite was successfully launched, signifying the introduction of the 55th satellite within the Beidou family. The third iteration of the Beidou Navigation Satellite System provides full global coverage for timing and navigation, offering an alternative to Russia's GLONASS,[313] the European Galileo positioning system,[314] and the US's GPS.[315] According to China Daily, in 2015, fifteen years after the satellite system was launched, it was generating a turnover of US$ 31.5 billion per annum for major companies[316] such as China Aerospace Science and Industry Corporation, AutoNavi Holdings Ltd., and China North Industries Group Corp.[317] The industry witnessed consistent growth, averaging over 20% in value annually, reaching $64 billion in 2020, according to Xinhua data.[318] Domestic industry reports forecast the satellite navigation service market output value,[319] directly generated and driven by the Beidou system, will be worth 1 trillion yuan (US$ 156.22 billion) by 2025, and US$ 467 billion by 2035.[320]In BeiDou-3, the third phase of the BeiDou system (BDS-3) comprises three GEO satellites, three IGSO satellites, and twenty-four MEO satellites. This expansion introduces new signal frequencies: B1C/B1I/B1A (1575.42 MHz), B2a/B2b (1191.795 MHz), B3I/B3Q/B3A (1268.52 MHz), and Bs test frequency (2492.028 MHz).Interface control documents detailing the new open signals were published between 2017 and 2018.[321] On June 23, 2020, the deployment of the BDS-3 constellation was successfully completed after the final satellite launch at the Xichang Satellite Launch Center[322]. BDS-3 satellites[323] also incorporate SBAS (B1C, B2a, B1A - GEO sats)[324], Precise Point Positioning (B2b - GEO sats), and search and rescue transponder (6 MEOSAR) capabilities.[325]

Regional Navigation Satellite Systems (GNSS)

Japan's Quasi-Zenith Satellite System (QZSS): This is a satellite-based augmentation system for GPS, designed to enhance GPS accuracy in the Asia-Oceania region[326] and plans for a GPS-independent satellite navigation system are set for 2023.[327] It's a regional satellite navigation system, consisting of four satellites, and also serves as a satellite-based augmentation system created by the Japanese government to improve the performance of the US-operated GPS in the Asia-Oceania area, particularly in Japan.[328] The primary objective of QZSS is to deliver highly precise and stable positioning services within the Asia-Oceania region while remaining compatible with GPS.[329] Trial services with four QZSS satellites commenced on January 12, 2018[330], and they were officially launched on November 1, 2018.[331] There are plans to establish a satellite navigation system independent of GPS by 2023, featuring seven satellites.[332] In May 2023 it was announced that the system would expand to eleven satellites.[333]The mentioned QZSS TKS technology represents an innovative satellite timekeeping system that eliminates the need for on-board atomic clocks, unlike existing navigation satellite systems such as BeiDou, Galileo, the Global Positioning System (GPS), GLONASS, or the NavIC system.[334] Further details and operational insights can be found in the reference videos.[335,336]

Indian Regional Navigation Satellite System (IRNSS): IRNSS is the operational moniker for NavIC (Navigation with Indian Constellation), which translates to "nāvik" or "sailor" or "navigator" in Hindi languages.[337] This independent regional satellite navigation system offers precise real-time positioning and timing services.[338] It covers India and a region extending 1,500 km around it, and it has plans for further extension. There are intentions to expand its coverage further. An extended service area lies between the primary service region and a rectangular area defined by the 30th parallel south to the 50th parallel north and the 30th meridian east to the 130th meridian east.Additionally, there exists a zone spanning 1,500–6,000 kilometers beyond borders, where some NavIC satellites are visible, although position accuracy cannot always be guaranteed.[339] Currently, the system comprises eight satellites in orbit, with two additional satellites on standby, deployed by India.[340] It has deployed by India.[341] The constellation is in orbit as of 2018.[342] . NavIC will offer two service tiers: the "standard positioning service," accessible for civilian use, and a restricted, encrypted service designated for authorized users, including the military.[343] In India, NavIC-based trackers are mandatory for commercial vehicles[344], and consumer mobile phones[345] with NavIC support have been available since the first half of 2020.[346] Plans are in place

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to augment the NavIC system by increasing the constellation size from 7 to 11 satellites.[347] Comprehensive information and operational details can be found in the referenced videos.[348,349]

In India's Department of Space's 12th Five Year Plan (FYP) covering 2012–17, it was outlined that the satellite [350] constellation would be expanded from 7 to 11 to extend its coverage.[351] These four additional satellites will be constructed during the 12th FYP and will be launched at the outset of the 13th FYP into a geosynchronous orbit with a 42° inclination.[352] Concurrently, efforts were initiated to develop space-qualified Indian-made atomic clocks. There was also an initiative to study and develop an all-optical atomic clock with ultra-stable capabilities suitable for IRNSS and deep space communication.[353] The Indian Space Research Organization (ISRO)[354] is set to launch five next-generation satellites featuring new payloads and an extended lifespan of 12 years.[355] These five new satellites, namely NVS-01, NVS-02, NVS-03, NVS-04, and NVS-05, will complement and enhance the existing satellite constellation. They will introduce the L5 and S bands and incorporate a new interoperable civil signal in the L1 band within the navigation payload. These satellites will utilize the Indian Rubidium Atomic Frequency Standard (iRAFS)[356] The introduction of this new L1 band will facilitate the proliferation of NavIC in wearable smart devices and IoT applications, offering a low-power navigation system. NVS-01 is slated to replace the IRNSS-1G satellite and is scheduled for launch on GSLV in 2023.[357] A study and analysis for the Global Indian Navigation System (GINS) was launched as part of the technology and policy initiatives during the 12th FYP (2012–17.[358] This envisioned system is designed to feature a constellation of 24 satellites positioned 24,000 kilometers (14,913 miles) above Earth. By 2013, the statutory filing for frequency spectrum allocation for GINS satellite orbits in international space had been completed.[359] According to the new 2021 draft policy, ISRO and the Department of Space (DoS) are collaborating to expand the coverage of NavIC from regional to global.[360] This global system will operate independently of other operational systems like GPS, GLONASS, BeiDou, and Galileo, while maintaining interoperability and offering free access for global public use.[361] ISRO has proposed to the Government of India to kickstart the process by initially placing twelve satellites in MEO to achieve global coverage.

Augmentation of GNSS

GNSS augmentation is a technique employed to enhance the attributes of a navigation system, including precision, reliability, and availability, by incorporating external data into the calculation process. Various such systems are in operation, typically categorized or named based on how the GNSS sensor receives external data. Some systems transmit supplementary information regarding error sources (such as clock drift, ephemeris data, or ionospheric delay), while others furnish historical measurements of signal deviations. A third group offers additional vehicle data for integration into the calculation process. GNSS receivers utilize GNSS augmentation to yield more precise positioning and timing results.Through real-time signals from GNSS satellites, GNSS receivers can ascertain their location (longitude, latitude, and altitude) with a few-meter accuracy. Nonetheless, these signals can benefit from support provided by Satellite-based Augmentation Systems (SBAS), Ground-based Augmentation Systems (GBAS), or Differential GNSS (DGNSS). These augmentation systems play a pivotal role in enhancing accuracy in positioning, timing, and navigation. Augmented GNSS can be categorized into distinct types, depending on the augmentation source, whether it's ground-based, satellite-based, or derived from a network of reference stations. The augmentation procedures encompass three distinct types, as elucidated below.

Ground Based Augmentation System (GBAS). A Ground-Based Augmentation System (GBAS) is a system that utilizes ground-based reference stations to offer differential corrections and ensure the integrity of Global Navigation Satellite Systems. This is commonly referred to as Differential GPS (DGPS) and is also known as Differential GNSS (DGNSS).[362]The differential correction data, derived from received information, is continuously broadcast in all directions (twice every second) via a ground transmitter using a VHF frequency broadcast (VDB). This broadcast is effective within an approximate 23 nautical mile radius around the host airport. GBAS primarily serves the purpose of enabling GNSS-based precision approaches.The primary objective of GBAS is to deliver signal integrity and accuracy, demonstrating position errors of less than one meter in both the horizontal and vertical dimensions.

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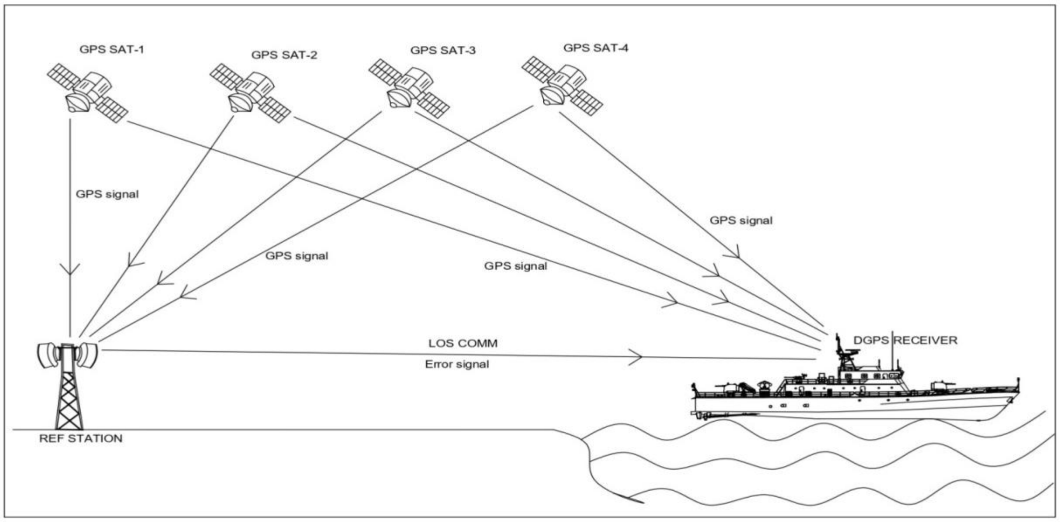

Figure 7: Example of image for Ground Based Augmentation System (GBAS)[363]

Mathematical Basis and Calculation. Consider the precise coordinates of the reference station are (x_o, y_o, z_o) and the base station coordinates for the insight GPS satellite are (x*b y*b z*b) retrieved in real time.

Hence, the differential co-ordinate correction can be expressed as

$$\left.\begin{array}{l} \Delta x= x^*_b-x_o \\ \Delta y=y^*_b-y_o \\ \Delta z=x^*_b-z_o \end{array}\right\} \text{---} \ (1)$$

These correction signals (Δx, Δy, Δz) are sent from the base station via radio connection to the surrounding region. Again, for the same group of satellites, the user's current position is (x^*_u, y^*_u, z^*_u). In addition, the user was also provided with the differential correction signal (Δx, Δy, Δz).

Hence, after giving the differential correction the actual position of the user will be

$$\left.\begin{array}{l} x_u = x^*_u- \Delta x \\ y_u=y^*_u-\Delta y \\ z_u =z^*_u-\Delta z \end{array}\right\} \text{-------------------------} \ (2)$$

According to the equation (2) the DGPS receiver will show the user's accurate position ($x_u y_u z_u$). Since GBAS relies on LOS (Line-of-sight) communication, its range is restricted (Aprox-20) because of the curvature of the earth.

Near an Airport, GBAS provides Differential GPS (DGPS) corrections and integrity verification, providing approaches like, for runways without ILSs. Within 23 nmi (43 km), corrections to GPS errors are delivered at 2 Hz through VHF data broadcast (VBD), measured by reference receivers at surveyed positions. Unlike an ILS, which requires separate localizer and glideslope antennas at each end of the runway, a single GBAS may handle up to 48 approaches and can be placed at a greater variety of locations along the runway. With the use of a GBAS, there are a number of ways to lessen the effects of wake turbulence and develop resilience by maintaining availability and running operations smoothly.[364]While the FAA committed US$ 2.5 million to evaluate the technology, the Port Authority of New Yark and New Jersey funded US$2.5 million to install a GBAS at Newark Airport (EWR)[365] in December 2008, Continental (now United) equipped 15 aircraft US$1.1 million.[366] The FAA accepted Honeywell's SLS-4000 GBAS design in September 2009, and it is still the only one.[367]It is capable of Cat. 1 instrument landings at a decision height of 200 ft (61 m) and may be improved to a height of 100 ft (30 m) Cat. 2 with real-time monitoring of ionospheric conditions through SBAS, Cat. 3 SLS-5000 is waiting for more compatible aircrafts. Approval for the first installations came in 2012 (EWR) and 2013 in (Houston/IAH). Congestion at JFK and LaGuardia (LGA) airports in New York has prompted the Port Authority to propose a GBAS. Newark and Houston GBAS were upgraded to Cat. 2, Seattle-Tacoma, San Francisco SFO, JFK and LGA will be upgraded in the near future.[368]

There are 20 Honeywell GBAS installations around the world, the other US installations are: Honeywell's test facility in Johnson County, Kansas; the FAA Technical Center at Atlantic City International Airport, New Jersey; Boeing's test facility in Grant County, Washington; the B787 plant in Charleston International, South Carolina; and Anoka County–Blaine Airport near Minneapolis.[369]Bremen, Frankfurt, Málaga, and Zurich are among the European airports that are equipped. Airports in Chennai, Kuala Lumpur, Melbourne, Seoul-Gimpo, Shanghai-Pudong and Sydney have these installations in the Asia-Pacific region.[370] St. Helena in the South Atlantic, Punta Cana in the Dominican Republic and Rio de Janeiro–Galeão are few more.[371]In Russia, around 100 Cat. 1 GBAS landing system (GLS) installations using Russian-developed technology have been discovered. By March 2018, there were more WAAS LPV approaches reaching 200 ft (61 m) than Cat. 1 ILS approaches in the United States. 1 GBAS costs $3–4 million and $700,000 more for Cat. 2. By Spring 2018, Boeing had delivered 3,500 GLS-capable aircraft, with another 5,000 on order: GLS Cat. 2/3 is standard on the Boeing 747-8, 787, and 777, while GLS Cat. 1 is optional on the 737NG/MAX, and GLS Cat. 2/3 will be available beginning in 2020. GLS Cat. 1 with Autoland is available on Airbus' A320, A330, A350, and A380.

To boost airport capacity and to reduce noise and weather delays, FAA's NextGen promotes the GBAS and GLS.[372] Boeing supports FAA assistance over cash, whereas the National Air Traffic Controllers Association claims that strict approaches will reduce traffic management flexibility, resulting in reduced throughput and capacity, a point of view shared by Delta Air Lines. Some members of the International Air Transport Association (ICAO) vetted GBAS Approach Service Types-D (GAST-D), which helps Cat. 2/3 aircraft landing and approach.[373] Safety requirements for GBAS systems are stricter than those for SBAS systems because GBAS is mostly used for landing, where real-time accuracy and signal integrity control are very important. This is especially true when the weather gets so bad that there is no visibility (CAT-I/II/III conditions), which SBAS is not designed or suitable for.[374]The US National Differential GPS System (NDGPS) was an enhancement system for users on land and sea in the US. NASA made the Global Differential GPS System (GDGPS), which is its replacement. It works with a lot more GNSS networks than just GPS. The same GDGPS system underlies WAAS and A-GNSS implementation in the US.[375]Ground stations can also be used to get ongoing GNSS readings, which can be used to correct data to the centimeter level after the fact. The US Continuously Operating Reference Stations (CORS) and the International GNSS Service (IGS) are two systems that work in this way.[376]

Satellite Based Augmentation (SBAS). In SBAS, rather than providing the error signal directly, a second geostationary satellite acts as a repeater, allowing it to overcome GBAS's limited coverage area. Existing GNSS systems may use a network of precisely located ground stations as their points of reference. The GNSS error can be computed by using the established locations of these reference/ground stations. This data is acquired at each reference/ground station, transferred to a central point, and then broadcasted over an entire region by geostationary satellites as an augmentation to the original GNSS signal. These signals can be used by GNSS modules to fix errors and provide more precise position information. It is retransmitted through the geostationary satellite. SBAS increases the accuracy, availability, and reliability of GNSS information by correcting signal measurement errors and providing information about the accuracy, integrity, continuity, and availability of its signals, resulting in position inaccuracies of less than 1m. Many countries implemented their own SBAS. Each satellite-based augmentation system is made up of three main parts.

- Ground segment. Such as reference station, muster station, uplink station.
- Space segment. Such as geostationary satellite as a repeater.
- User segment. It requires special receiver which is designed for that SBAS.

A SBAS improves GNSS performance by providing information on range, integrity, and correction. The ground infrastructure in SBAS consists of precisely surveyed and geographically distributed sensor stations that receive data from primary GNSS satellites, as well as a Central Processing Facility (CPF) that computes integrity, corrections, and ranging data to form the SBAS signal-in-space (SIS). The SIS is then sent to receiving devices through geosynchronous Earth Orbit (GEO) satellites, which derive their location and time information using measurements and satellite positions from both the source GNSS constellation(s) and the SBAS GEO satellites.[377] SBAS systems are vital for applications requiring precision and integrity. During critical phases of aircraft flight, particularly final approaches, the International Civil Aviation Organization (ICAO) has made the use of SBAS and other GNSS augmentation systems compulsory. Most powerful and technologically advanced governments and organizations employ their own SBAS system to improve accuracy, availability, and reliability.[378] Example of these globallyapplied SBAS has been stated bellow. All of these SBAS systems employ a common global standard and are hence able to communicate with all standard GNSS receivers. As a result, a GPS system designed in the United States may take advantage of SBAS solutions established in Europe or Asia in order to improve operational accuracy.

- WAAS (Wide Area Augmentation System): It has been run by the US and Canadian Federal Aviation Administration (FAA).[379]
- EGNOS (European Geostationary Overlay Service): It has operated by ESSP, EU (on behalf of EU's GSA).[380]
- MSAS (Multifunctional Satellite Augmentation System): It operated by by Japan's Ministry of Land, Infrastructure and Transport Japan Civil Aviation Bureau (JCAB).[381]
- BD SBAS (BeiDou Satellite Based Augmentation System): It operated by China and commissioned in July 2020.[382]
- GAGAN (GPS Aided Geo Augmentation Navigation): It operated by the Airports Authority of India.[383] All ac registered by July 2021 authorized to be equipped with GAGAN. GPS and GEO Augmented Navigation (GAGAN)[384] to cover the Indian subcontinent, Korea and China also have SBAS Solutions.[385]

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- The QZSS (Quasi-Zenith Satellite System), operated by Japan, started initial operations in November 2018. QZSS also operates in a non-SBAS mode called PNT, essentially acting as extra GNSS satellites.[386]
- The SDCM (System for Differential Corrections and Monitoring), operated by Russia's Roscosmos.
- WAGE (Wide Area GPS Enhancement): It has operated by US dept of Defense for military use and authorized receivers.
- GPS-C (C- Correction): It operated by Canada.
- The SouthPAN (Southern Positioning Augmentation Network), being established by Australia and New Zealand with initial services expected in 2022.[387]It is a 2nd Gen SBAS and operated by Australia and New Zealand.
- The commercial StarFire navigation system,[388] operated by John Deere and C-Nav Positioning Solutions (Oceaneering).[389]
- The commercial Starfix DGPS System and OmniSTAR system,[390] operated by Fugro.[391]
- The commercial Atlas GNSS Global L-Band Correction Service system,[392] operated by Hemisphere GNSS.[393]
- The GPS·C, short for GPS Correction, was a differential GPS data source for most of Canada,[394] maintained by the Canadian Active Control System, part of Natural Resources Canada and at present decommissioned.[395]
- The Australian SBAS using the Inmarsat 4F1 geostationary satellite,[396] which suffered an outage in April 2023.[397]

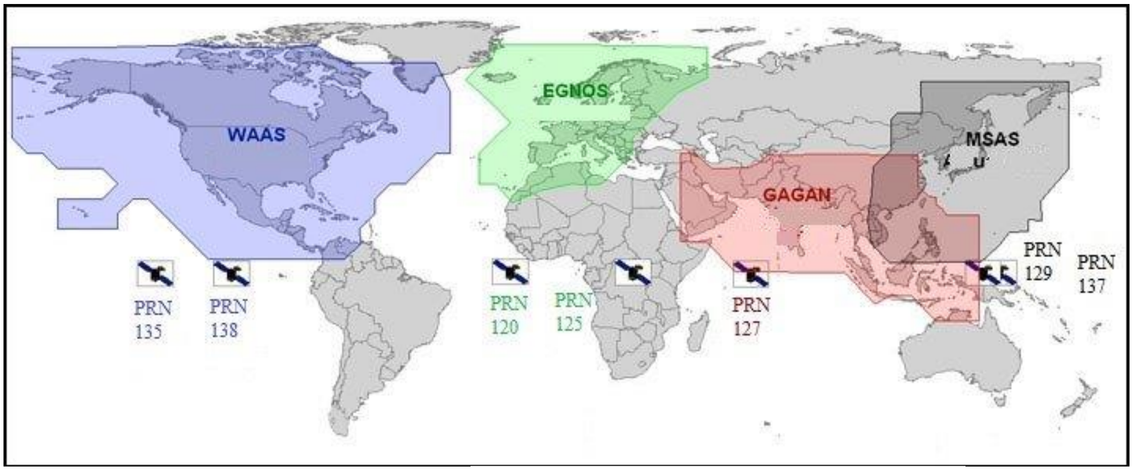

Figure 8: Different worldwide Satellite Based Augmentation System (SBAS)[398]

However, few commercial products of SBAS solutions can be discussed. U-blox's NEO-F9P is a multiband GNSS module designed for high-volume industrial applications. It can simultaneously receive signals from the constellations of GPS, GLONASS, Galileo, and BeiDou, and it integrates L1/L5 RTK technology for centimeter-level precision.[399]This module employs protected interfaces, advanced jamming, spoofing, and mitigating detection technologies to guarantee the security of location and navigation data. It offers a variety of open correction services, allowing each application to tailorits performance to its specific needs. This module consumes 72 mA of current and needs a DC source between 2.7 and 3.6 V. The NEO-F9P can be controlled via UART, SPI, USB and DDC (I2C compliant) interfaces. It is well-suited for mass market adoption due to its small package size, light weight and moderate power utilization, as well as its simple design, low design-in costs and minimal eBOM. This module is available in a 24-pin LCC package measuring 12.0 x 16.0 x 3.6 mm and is ideal for use in navigation and automation systems for mobile industrial machinery.[400]

Quantic Wenzel, a company that set the standard for ultra-low phase noise crystal oscillators, offers a broad portfolio of advanced capabilities and technologies to support commercial and defense radar applications, in addition to a range of advanced frequency sources and integrated microwave assemblies to 30 GHz and beyond.[401]These new sophisticated technologies have pushed the technological boundaries of what is possible with radar by refining designs, thereby spurring innovation in the defense radar domain. For today's mission-critical radar applications, compact, lightweight, power-efficient, and cost-effective RF/MW solutions with high performance are required. Quantic Wenzel develops low-phase noise and low-g sensitivity technologies into SWaP-C efficient, cost-effective RF/MW solutions. Engineers at Quantic Wenzel recognize that mission-critical program requirements are financially and strategically significant to the company, and they take their responsibility to assist clients in attaining their objectives very seriously. Quantic provides proactive, world-class client service from prototype to production in their efforts to develop and implement innovative RF/MW solutions with market-leading performance.[402]Quantic Wenzel serves the mission-critical RF/MW engineering and production requirements of some of the world's leading corporations. Their new ideas like frequency sources, are used by some of the biggest companies in the defense and business industries. They are put on platforms on the ground, in the air, on ships, and in space for long-, medium-, and short-range radar systems.[403]SBAS can provide wide-area or regional augmentation by using extra satellite-broadcast messages. Correction messages are prepared using measurements from ground stations and delivered to one or more satellites for broadcast to end users as differential signal. SBAS and WADGPS, wide-area differential GPS, are sometimes synonymous.[404]

Aircraft Based Augmentation (ABAS). The International Civil Aviation Organization (ICAO) refers to aircraft-based Augmentation Systems (ABAS) as a form of augmentation. ABAS may involve the integration of additional information from navigational sensors into the position calculation or the implementation of internal algorithms that enhance navigation performance.[405] Many times the additional avionics operate via separate principles from the GNSS and are not necessarily subject to the same sources of error or interference.[406]A system such as this is referred to as an aircraft-based augmentation system (ABAS) by the ICAO.[407]The most widely used form of ABAS is receiver autonomous integrity monitoring (RAIM).[408]It uses redundant GPS signals for detecting the faulty signals and ensuring the integrity of the position solution.[409] Additional sensors may include:

eLORAN receivers. LORAN receivers are an electronic version of the long range navigation system (LORAN) developed in the United States during the Second World War.[410]The LORAN system was developed in response to the Gee system developed by the United Kingdom, which operated at a lower frequency to provide an increased range of 10,000 miles (15,000 km). Initially, LORAN was used for the transportation of ship convoys across the Atlantic Ocean and then for long-distance patrol aircraft. However, it was primarily used on ships and aircraft in the Pacific Theater of World War II.[411] and is now available as an automated celestial navigation system (ELORAN).ELORAN is a form of celestial navigation that utilizes the position fixing power of the stars and other heavenly bodies to accurately determine a navigator's current physical position, rather than relying solely on estimates of position, such as dead reckoning, which is not supported by satellite navigation or modern electronic and digital positioning systems.

Automated celestial navigation systems. Astronavigation, also known as celestial navigation, is the process of fixing positions using stars and other heavenly bodies. It's a way for a navigator to know exactly where they are in the sky or on the ground, without having to rely on guesswork like dead reckoning.[412]It's done without the need for satellite navigation or other fancy electronic or digital positioning systems.[413]

Inertial navigation systems. Inertial Navigation Systems (INS), also known as Inertial Guidance Systems (IGS), is a type of navigational device that uses inertial sensors such as accelerometers, gyroscopes, etc. to continuously calculate the position, orientation, and velocity (direction, speed, and so on) of the moving object without external reference data.[414] Often the inertial sensors are supplemented by a barometric altimeter and sometimes by magnetic sensors (magnetometers) and/or speed measuring devices. INSs are used on mobile robots[415]and on vehicles such as ships, aircraft, submarines, guided missiles, and spacecraft.[416]

Distance measuring equipment. DME (Distance Measuring Equipment) is a radio navigation technology used in aviation to measure the angle of difference (slant) between aircraft and ground stations by timing propagation delays of radio signals within the frequency band (MHz) from 960 to 1215 MHz. It is essential for line-of-sight between aircrafts and ground stations.[417]

Simple dead reckoning systems. It comprised of gyrocompass and distance measurement. Dead reckoning in navigation is the method of determining the current location of an object by reference to a fixed position or fix and estimates of velocity, direction or course, and time elapsed. Path integration is a related term in biology to describe the process by which an animal changes its estimate of position or direction.[418]

Future of GNSS

GPS modernization began with SA being decommissioned in 2000, followed by the launch of a new civil code on the L2 (L2C) frequency, then the third civil frequency L5. The next step is to evaluate and design the next generation of satellites, which will meet military and civilian needs through 2030. Led by Lockheed Martin and now by Boeing, the team has had some success with the launch of the first of the new GPS III satellites. One of the biggest advantages of using GPS, GALILEO, and GLONASS at the same time is that availability is improved, especially in cities, which shows how successful satellite communication is.[419]On the other hand, the ability of GALILEO and GPS to work together as a mutual backup improves reliability when one of the systems is out of commission. The fact that more satellites have launched in recent years means that a certain level of accuracy is now achieved. The accuracy of positioning is less affected by satellite geometry. The impacts of multipath (interference/jamming) are reduced and indicated measurement quality increases. GPS, GLONASS, BeiDou and GALILEO are independent GNSS systems, which mean major system problems are a very remote possibility of occurring simultaneously.[420]Once again, L2 GPG measurements by survey grade receivers are noisy and less consistent than the measurements expected to be performed on one of the new L2C (or L5) signals; hence, reliable dual frequency operation has already improved. There will be an effect on efficiency (time to ambiguity resolution), as not all frequencies /codes can be monitored. It is important to note that newer systems with improved electronics & antennas in satellites & user receivers will deliver overall improved data quality. For carrier phase based positioning, with centimeter accuracy the additional satellite signals will greatly reduce the time needed to resolve ambiguities. The density of GNSS reference stations will also significantly reduce in support of differential positioning with triple frequency techniques.[421]

Improving UERE will improve SPS standalone accuracy, and it'll also help us to get a better first receiver position to do ambiguity resolution.[422]The accuracy of the first receiver position and UERE will also affect how we estimate float ambiguities, and a better estimation will make it easier to fix integer ambiguities. It's hard to resolve ambiguities directly on L1 / E1 because the wavelengths are so small that measurements of L1 /E1 are prone to ionospheric and other errors. But if we use the right combination of phases on both carrier frequencies, it could have advantages like a longer wavelength and less sensitivity to ionospheric or other errors, making it easier to fix ambiguities than it would be for L1 / E 1 ambiguities.[423]We can also use triple frequency combinations to eliminate the

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effect of ionospheric delay, which will improve the accuracy of the measurement.[424]Now we have three frequencies and more combinations between the phases on different carrier frequencies.[425]

As the number of systems and signals increases, so it reduces the error rate. Even basic navigation receivers are now errorless.[426] Today, smart phones are a few meters away from the correct location in most places.[427]In the next few years, we'll see centimeter-scale accuracy for mass market devices like smart-phones, too. Projects like GALILEO will make this possible for most users.[428] Some specialized users may not even need to use high accuracy devices, which are typically much more expensive. In fact, the ability to have a Smart-phone could allow for very accurate mapping. Devices like UAVs, and autonomous vehicles are also starting to adopt better GNSS signals, from multiple frequency bands. Safety is still a top priority, especially maintaining a secure signal that isn't hacked or disrupted. Open signal navigation services already provide authentication services to avoid spoofing and jamming or the sending and receiving of false signals or interfering with the position GNSS signal. This is important for safety and for financial services that rely on GPS, where authentic signals need to be maintained all the time. While GNSS receivers have been increasingly adapted to handle the multiple signals that are used by the current satellite constellation; future satellite design is evolving as multi signal location services become increasingly common.[429] In fact, it's not just the satellite-based system that's evolving, but the ground-based network that's being used to improve the system and work with the navigation devices.[430] In the case of high-accuracy systems, this could mean that devices will become much cheaper as smaller devices become capable of providing accuracy at levels of detail that can be done with detailed mapping. Mass produced high-accuracy GNSS will open up new markets, and then industries like autonomous vehicles and financial services and others we haven't even thought of yet could benefit greatly from the introduction of low-cost GNSS receivers in the near future. GPS positioning will not only work together with other location services, but it will also be more accurate than existing capabilities. This will allow for improved mapping and navigation features on devices that rely on high precision. With improved precision and more signals available, mass-market navigation receivers will be almost or even as precise as current high-precision devices like DGPS. It could open up new industries and consumer opportunities we never thought possible.[431]

Conclusion

In 1983, U.S. President Ronald Reagan authorized the service for civilian use. However, in order to gain a military advantage, he restricted the accuracy of the service with a feature known as Selective Availability. This was a deliberate degradation of GPS. Instead of providing precise location information, civilian GPS was only accurate within a range of 50 meters. Subsequently, with the development of new technologies, Selective Availability was removed by President Bill Clinton in May 2000. Nowadays, GPS is precise for civilian use. The GPS is the United States' satellite-based positioning and navigation system. Recipients on or near the Earth's surface can be located by interpreting signals received from any of the four or more satellites in the network. All GPS satellites broadcast on the same two frequencies, known as L1 (1575.42 MHz) and L2 (1227.60 MHz). The network is characterized by the use of CDMA (code-division multiple access), which allows separate messages to be distinguished from the individual satellites. CDMA encodings use two encodings: the C/A encodings, which the general public can access, and the precise encodings (P), which are encrypted and can only be accessed by the US military. Many people mistakenly confuse GNSS with GPS, as both seem to be global positioning systems that can locate an object's location. GNSS is a generic term for a satellite-based navigation system that determines the position, navigation and timing used in various applications. GPS, also known as North American GNSS, is the name of a global positioning system (GPS). A satellite navigation system (satnav) is a network of satellites that provides independent geo-positioning services. A global navigation system (GNSS) with global coverage is also known as a global satellite navigation system. As of 2023, there are four global systems in operation: the US's GPS, the Russian's GLONASS, the Chinese's BeiDou and the EU's Galileo. Enhancement techniques are based on the integration of external information into the calculation. There are many of these systems, and they are typically named or described according to how the GPS sensor interprets the data. Some transmit additional information on sources of error (like, clock drift or ephemeris, ionospheric delay, etc.), others provide direct measurement of how far off the signal has been in the past, and a third group provides supplementary navigational or vehicle data to be incorporated into the calculation.

GNSS uses radio signals from satellites to send out time signals that small electronic receivers can use to determine their position (latitude, longitude and altitude) up to a few meters away. The receivers on land, air or water can then calculate the exact time and position. This can be used for scientific experiments as well as for many daily applications. Currently, the four full-functioning global GNSS systems are GPS (US), GLONASS (Russia), GALILEO (EU) and BeiDou (China). The global coverage of each system is usually achieved through a constellation of about 24–30 MEO satellites distributed among several orbital planes, with an average orbit inclinations over 50° and an orbital period of about 12 hours (20,000 km or 12,500 mi). The regional systems QZSS (Japan) and IRNSS (India) utilize satellites at smaller inclinations in elliptical orbits with apogees around 24,000 and 39,000 km or in inclined geostationary orbits at around 36,000 km. The more satellites a receiver can observe, the more accurate the position, time or speed measurements become. This is the reason for WAAS in the US, SDCM in Russia, EGNOS in the EU, GPS and GPS/GAGAN in India, and MTSAT/SBAS in Japan. Today, there are over 120 GNSS satellites in orbit. Today, a user can receive signals from up to ten satellites, resulting in accuracies that are only available at research level. The current GPS has been in development for 30 years.

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The original motivation was for military use only, but over the last few decades GPS has been used for civilian applications as well. The integrity, availability and accuracy of GPS still need to be improved for various applications, which is why a GPS modernization was launched in the late 90’s to improve the performance of GPS for civilian and military use. Right now, GPS is being upgraded in the US, GLONASS is being refreshed in Russia, BeiDou is being developed in China, and GALILEO is being developed in Europe. Japan's QZSS and India's GAGAN are also getting better and faster. The extra satellites will help improve performance for all kinds of applications, especially in places where satellite signals can't be seen, like in canyons, trees, inside buildings, caves, or even in mines. The advantages of the extra satellites and the signals they'll send out can be broken down into things like availability, accuracy, reliability, continuity, efficiency, and resolving ambiguities. All the findings in this study show that the future of GNSS will have huge benefits that will affect every aspect of our lives in the 21st century.

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