A REVIEW OF GLOBAL NAVIGATION SATELLITE SYSTEMS (GNSS) AND ITS APPLICATIONS

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Abstract— *Right from the early stages of human evolution, positioning and navigation has been of paramount importance to human existence. The increase in the complexity of human activities led to the development of the Global Navigation Satellite System (GNSS). Aside from being a major player in the defence and other military applications, GNSS has so many applications in other fields like surveying, precision farming, transport industry, mining et cetera. Hence in this work GNSS origin, GNSS types, GNSS signal and frequencies of propagation, and GNSS applications will be comprehensively reviewed.*

Index Term — Applications, BEIDOU , GALILEO, GLONASS, , GNSS, GPS, Review, Satellite-Systems

1.0 Introduction

Throughout the history of human evolution and civilizations, even before the advent of the advanced Global Navigation Satellite System (GNSS), humans have developed various positioning systems and it could be said that it was an ultimate measure to compete and survive against other animals with superior sensory organs [1]. For instance when humans are hunter-gatherers, if they had not been able to accurately locate prey and other sources of livelihood, the human evolutionary process would have been truncated long ago and would have gone into extinction. They would even need more accurate positioning ability as they travel farther from their homes, and the advancements in the positioning greatly help in expanding their radius of activities [1]. Later on, as people began sailing the oceans, instruments such as the Sextant were developed and adopted for many years. It was developed using the knowledge people had in geometry and the error associated with its usage depending on the experience and competency of the user. As good and accurate as the Sextant was, it was impossible to use it under certain conditions [1]. The need for an accurate position system that could work under all types of weather condition gave rise to the radio position systems such as the DECA, LORAN and OMEGA. They are electromagnetic waves of very low frequency. The advancement in electronics and space technology led to the development of Navigation Satellite Systems such as the GPS, GLONASS, etc. [1].

2.0 History and Origin of GNSS

The Global Navigation Satellite System (GNSS) is a constellation of satellites stationed at the Medium Earth Orbit (MEO) that transmits positioning and timing data to GNSS receivers [2]. These satellites are used in obtaining the position of stationary and moving objects and find great applications in surveying, geology, geography, geophysics, navigation, robotics, and various other purposes. The constellation consists of the United States of America's GPS (Global Positioning System), Russia's GLONASS (Global'naya Navigatsionnaya

Sputnikovaya Sistema), China's BeiDou Navigation Satellite System, and the European Union's GALILEO. The first satellite navigation system named SPUTNIK was launched by the Soviet Union on October 4, 1957 [3]. After successful deployment into space, the first satellite (Sputnik I) failed and fell back to the earth, another artificial satellite was launched (Sputnik II) months later which was successfully parked in orbit of the earth. The unanticipated success of the Sputnik Missions sparked the beginning of the space race which was part of the cold war between America and the Soviet Union [3].

TRANSIT, a satellite navigation system was deployed by the US military on April 13, 1960. TRANSIT's operation was based on the Doppler Effect: the satellites travelled on well-known paths and broadcast their signals on a well-known radio frequency. The received frequency will differ slightly from the broadcast frequency because of the movement of the satellite with respect to the receiver. By monitoring this frequency shift over a short time interval, the receiver can determine its location to one side or the other of the satellite, and several such measurements combined with precise knowledge of the satellite's orbit can fix a particular position. Satellite orbital position errors are induced by variations in the gravity field and radar refraction, among others. These were resolved by a team led by Harold L Jury of Pan Am Aerospace Division in Florida from 1970-1973. Using real-time data assimilation and recursive estimation, the systematic and residual errors were narrowed down to a manageable level to permit accurate navigation [3].

3.0 Propagation of GNSS Signals

Radio waves do not travel in a straight path. Light travels in a straight line only in a vacuum or through a perfectly homogeneous medium. Just as straw is seemingly "bent" in a glass of water, radio signals from the satellite are bent as they pass through the earth's atmosphere. This "bending" increases the amount of time the signal takes to travel from the satellite to the receiver. The distance to the satellite is calculated by multiplying the time of propagation (which, you recall, is the time it takes the signals to travel from the satellite to the receiver) by the speed of light. Errors in the propagation time increase or decrease the computed range to the satellite. Incidentally, since the computed range contains errors and is not exactly equal to the actual range, it refers to a "pseudo-range" [4].. The layer of the atmosphere that most influences the transmission of GNSS (and other augmentation satellite signals) is the ionosphere, the layer 70 to 1,000 km above the earth's surface. Ultraviolet rays from the sun ionize gas molecules in this layer, releasing free electrons. These electrons influence electromagnetic wave propagation including GPS satellite signal broadcasts. Ionospheric delays are frequency dependent so by calculating the range using both L1 (1575.42MHz) and L2 (1227.6MHz), the effect of the ionosphere can be virtually eliminated by the receiver. The other layer of the atmosphere that influences the transmission of GPS signals is the troposphere, the lowest layer of the Earth's atmosphere. The thickness of the troposphere varies, about 17km in the middle latitudes, up to 20 km nearer the equator, and thinner at the poles. Tropospheric delay is a function of local temperature, pressure and relative humidity. L1 and L2 are equally delayed, so the effect of tropospheric delay cannot be eliminated the way ionospheric delay can be. It is possible, however, to model the troposphere then predict and compensate for much of the delay [4]. Some of the signal energy transmitted by the satellite is reflected on the way to the receiver. This phenomenon is referred to as "multipath propagation." These reflected signals are delayed from the direct signal and, if they are strong enough, can interfere with the desired signal. Techniques have been developed whereby the receiver only considers the earliest-arriving signals and ignores multipath signals, which arrive later. In the early days of GNSS, most errors came from ionospheric and tropospheric delays, but now more attention is being made to multipath effects, in the interests of continually improving GNSS performance.

4.0 GNSS Signal Reception

Receivers need at least four satellites to obtain a position. The use of more satellites, if they are available, will improve the position solution; however, the receiver's ability to make use of additional satellites may be limited by its computational power. The manner by which the

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receiver uses the additional ranges will generally be the intellectual property of the manufacturer. To determine a fix (position) and time, GNSS receivers need to be able to track at least four satellites. This means there needs to be a line of sight between the receiver's antenna and the four satellites.

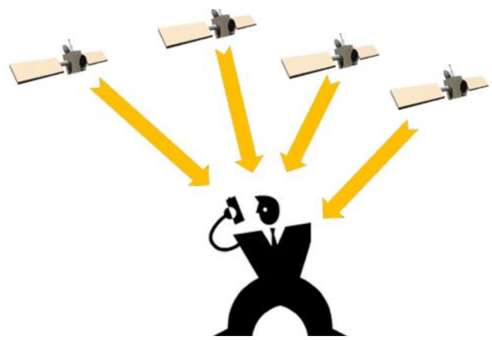

Figure1: GNSS Signal Reception (Source: International Committee on GNSS)

5.0 Global Positioning System (GPS)

Global Positioning system (GPS) is a constellation of 24 satellites working together as a system to provide global or near-global coverage owned by the American government. The GPS satellites are placed at about 20200 km in the middle Earth orbit (MEO), the satellites are arranged in six equally spaced orbits to accommodate 4 satellites in each of the orbits. The system provides users with Position, Navigation, and Time (PNT) services [5]. The GPS constellation which was initially used for military purposes was released for civilian usage in 1983. The constellation which consists of 4 satellites parked in 6 orbits has a period of approximately 11 hours and 58 minutes round the earth and the orbit is inclined at 55^{o} with a transmission speed of 50bps [1]. The current GPS consists of three major segments: a space segment (SS), a control segment (CS), and a user segment (US). The space segment consists of the 24 nominal satellites that transmit one-way signals to give the current satellite position and time. Each plane orbital contains four "slots" occupied by baseline satellites. This 24-slot arrangement ensures users can view at least four satellites from virtually any point on the planet [5].

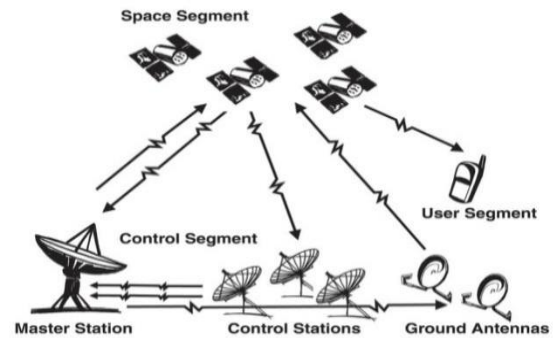

Figure 2: Schematic Diagram showing the operational Segments of GPS (Source: Google.com)

As at June 2011, GPS now effectively operates as a 27-slot constellation with improved coverage in most parts of the world [5]. GPS boosts productivity across a wide swath of the economy, including farming, construction, mining, surveying, package delivery, and logistical supply chain management. Major communications networks, banking systems, financial markets, and power grids depend heavily on GPS for precise time synchronization. Some wireless services cannot operate without it.

5.1 GPS Signals and Frequency

Table 5.1: GPS signals and Frequencies

System	Signal	Frequency (MHz)
GPS	L1 C/A	1576.42
GPS	L1 C	1575.42
GPS	L2 C	1227.6
GPS	L2 P	1227.6
GPS	L5	1176.45

The GPS satellites transmit several ranging codes and navigation data using the Binary Phase Shift Keying (BPSK). Since only limited central systems are used in the GPS system, satellites using the same frequency can only be identified and distinguished using the different ranging codes. In

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other words, the GPS uses the Code Division Multiple Access (CDMA). The C/A code refers to the Coarse and Acquisition code which is freely available to the public, while the restricted precision P-code is reserved for military usage.

6.0Global Navigation Satellite System (GLONASS)

GLONASS stands for Globanaya Navigationaya Sputnikovaya Sistema or Global Navigation Satellite System. It is Russia's version of the GPS (Global Positioning System) and it contains strictly 24 satellites in equally spaced orbits. It is often used in conjunction with the GPS to provide faster and more accurate positioning and timing [6]. The satellite constellation of GLONASS contains 24 operational satellites that are distributed over three orbital planes. The orbits are separated by an ascending node of 120^{o} from plane to plane. The satellite operates in a circular orbit that is at an altitude of 19100 km from the earth's surface and each of the 24 satellites completes an orbit in approximately 11 hours 15 minutes. GLONASS was first launched in 1982 by the Soviet Union. The first constellation contains 4 satellites that have a lifetime of 3 years. Each of the satellites has a mass of 1250kg and power of 1000W. The navigation system has two available services: the Standard Positioning Service (SPS) and the Precise Positioning Service (PPS). The SPS is an open service, free to use by all and sundry with the navigational signal provided in the frequency band G1 and recently changed to the second civil signal G2 in 2004. The Precise Positioning Service (PPS) is a high-accuracy signal that is restricted to military and authorized user's usage. The navigational signals are provided in two frequency bands G1 and G2 [7].

6.1 GLONASS Signals and Frequency

Table6.1: GLONASS Signals and Frequencies

System	**Signal**	**Frequency (MHz)**
GLONASS	L1 C/A	1598.0625 – 1609.3125
GLONASS	L2 C	1242.9375 – 1251.6875
GLONASS	L2 P	1242.9375 – 1251.6875
GLONASS	L3 OC	1202.025

7.0 GALILEO

GALILEO is a satellite navigation system that is owned and controlled by a host of countries on the continent of Europe. It is safe to say that it Europe's version of the GPS. The navigation system went live in 2016 and was named after the famed Italian astronomer, Galileo Galilei. It was created by the European Union (EU) through the European Space Agency (ESA) to provide an independent and highly accurate positional and navigational system so as to reduce/expunge the reliance of nations in the EU on GPS and GLONASS. When fully deployed, The GALILEO system will have 30 operational satellites which will provide a highly accurate and guaranteed global positioning service that is fully under civilian control [7].

7.1 GALILEO Signal and Frequency

Table 7.1:GALILEO's Signal and Frequencies

System	Signal	Frequency (MHz)
GALILEO	E1	1575.42
GALILEO	E5a	1176.45
GALILEO	E5b	1207.14
GALILEO	E5 Alt BOC	1191.795
GALILEO	E6	1278.75

Galileo satellites transmit permanently three independent CDMA and Right-Hand Circularly Polarised (RHCP) signals, named E1, E5, and E6. The E5 signal is further sub-divided into signals denoted E5a and E5b. These signals are transmitted in four frequency bands which provide wide bandwidth for the transmission of the Galileo signals. The Galileo E5 signal, with its Alternative Binary Offset Carrier (Alt BOC) modulation is one of the most advanced and promising signals of the Galileo system, it has unmatched performance in term of measurement noise and multipath robustness. E6 signals are modulated with a binary

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phase-shift keying BPSK at a carrier frequency of 1278.75 MHz, which is used by all satellites and shared through a CDMA RF channel access mode.

8.0 BEIDOU

The fourth GNSS system, joining those undertaken by the United States—GPS, Russia—GLONASS, and Europe—Galileo, will be the Chinese-BeiDou. The system is named after the Big Dipper. The first generation of the system is known as BeiDou-*1*. It is a regional satellite navigation system that services a portion of the Earth from 70°E longitude to 140°E longitude and from latitude 5°N to 55°N. It relies on 3 satellites with 1 backup. The first satellites were launched into geostationary (GEO) orbits in 2000; BeiDou-1A at 140º E longitude and BeiDou-1B 80º E longitude. A third satellite, BeiDou-1C joined them 3 years later at110.5º E longitude. With the launch of the fourth, BeiDou-1D in 2007 the first BeiDou-1 system was operational, regionally [7]. The first BeiDou-2 satellite, a medium Earth orbit (MEO) satellite named Compass-M1 was launched into a circular orbit at 21,500 km at an inclination of 55.5º. Similar satellites followed; and between 2007 and 2012, there were 5 MEO satellites with sequential names from Compass-M1 to M6 (without an M2) launched. During the period from 2009 to 2012, the 6 GEO BeiDou-2 satellites with sequential names from Compass-G1 to G6 were launched. Their positions are at 58.75°E longitude (G5), 80.0°E longitude (G6), 110.5°E longitude (G3), 140.0°E longitude (G1), 160.0°E longitude (G4). The G2 satellite is inactive [12].

8.1 BEIDOU Signals and Frequency

Table 8.1: BEIDOU Signals and Frequencies

System	**Signal**	**Frequency (MHz)**
BEIDOU (COMPASS)	B1l	1561.098
BEIDOU	B2l	1207.14
BEIDOU	B3l	1268.52
BEIDOU	B1c	1575.42
BEIDOU	B2a	1176.45
BEIDOU	B2b	1207.14

9.0 Applications of GNSS

9.0.1 Surveying

GNSS-based surveying reduces the number of equipment and labour required to determine the position of points on the surface of the Earth when compared with previous surveying techniques. Using GNSS, it is possible for a single surveyor to accomplish in one day what might have taken a survey crew of three people a week to complete. Using GNSS, surveyors can now set up a DGNSS or RTK base station over an existing survey point and a DGNSS or RTK rover over the new point, then record the position measurement at the rover. This simplification shows why the surveying industry was one of the early civilian adopters of GNSS technology [8].

Figure 3: Modern GNSS Survey Instrument
(Source: Alibaba.com)

9.0.2 Consumer

GNSS technology has been adopted by the consumer market, in an ever-increasing range of products. GNSS receivers are now routinely integrated into Smartphone's, to support applications that display maps showing the location of and th best route to stores and restaurants. Portable navigation devices give drivers directions on-road or off. Currently, most GNSS consumer products are based on GPS, but this will change as more GNSS constellations are implemented [8].

9.0.3 Transportation

In rail transportation, GNSS is used in conjunction with other technologies, to track the location of locomotives and rail cars, maintenance vehicles, and wayside equipment, for display at central monitoring consoles. Knowing the precise location of rail equipment reduces accidents, delays, and operating costs, enhancing safety, track capacity, and customer service. In aviation, GNSS is being used for aircraft navigation from departure, en route, to landing. GNSS facilitates aircraft navigation in remote areas that are not well served by ground-based navigation aids, and it is a significant component of collision avoidance systems, and of systems used to improve approaches to airport runways [5]. In marine transportation, GNSS is being used to accurately determine the position of ships when they are in the open sea and also when they are manoeuvring in congested ports. GNSS is incorporated into underwater surveying, buoy positioning, navigation hazard location, dredging, and mapping. In surface transportation, vehicle location and in-vehicle navigation systems are now being used throughout the world. Many vehicles are equipped with navigation displays that superimpose vehicle location and status on maps. GNSS is used in systems that track and forecast the movement of freight and monitor road networks, improving efficiency and enhancing driver safety [7].

9.0.4 Machine Control

GNSS technology is being integrated into equipment such as bulldozers, excavators, graders, pavers and farm machinery to enhance productivity in the real-time operation of this equipment, and to provide situational awareness information to the equipment operator. The adoption of GNSS-based machine control is similar in its impact to the earlier adoption of hydraulics technology in machinery, which has had a profound effect on productivity and reliability [8].

9.0.5 Precision Agriculture

In precision agriculture, GNSS based applications are used to support farm planning, field mapping, soil sampling, tractor guidance, and crop assessment. The more precise application of fertilizers, pesticides, and herbicides reduces cost and environmental impact. GNSS applications can automatically guide farm implements along the contours of the earth in a manner that controls erosion and maximizes the effectiveness of irrigation systems. Farm machinery can be operated at higher speeds, day and night, with increased accuracy. This increased accuracy saves time and fuel, and maximizes the efficiency of the operation. Operator safety is also increased by greatly reducing fatigue [8].

Figure 4: Precisely aligned Crop Row planted by GNSS-Guided Machinery (Source: Novatech)

9.0.6 Construction

GNSS information can be used to position the cutting edge of a blade (on a bulldozer or grader, for example) or a bucket (excavator), and to compare this position against a 3D digital design to compute cut/fill amounts. “Indicate systems” provide the operator with visual cut/fill information, via a display or light bar, and the operator manually moves the machine’s blade or bucket to get to grade. Automatic systems for bulldozers/graders use the cut/fill information to drive the hydraulic controls of the machine to automatically move the machine’s blade to grade. Use of 3D machine control dramatically reduces the number of survey stakes required on a job site, reducing time and costs. productivity studies have repeatedly shown that the use of 3D machine control results in work being completed faster, more accurately, and with significantly less rework than conventional construction methods [9].

9.0.7 Surface Mining

GNSS information is being used to efficiently manage the mining of an ore body and the movement of waste material. GNSS equipment installed on shovels and haul trucks provides position information to a computer-controlled dispatch system to optimally route haul trucks to and from each shovel. Position information is also used to track each bucket of material extracted by the shovel, to ensure that it is routed to the appropriate location in the mine (crusher, waste dump, leach pad). Position information is used by blast hole drills to improve fracturization of the rock material and control the depth of each hole that is drilled, to keep the benches level. Multi-constellation GNSS is particularly advantageous in a surface mining environment due to the obstructions caused by the mine’s walls. More satellites mean more signal availability [10].

9.0.8 Time Applications

As mentioned in earlier chapters, time accuracy is critical for GNSS position determination. This is why GNSS satellites are equipped with atomic clocks, accurate to nano- seconds. As part of the position determining process, the local time of GNSS receivers becomes synchronized with the very accurate satellite time. This time information, by itself, has many applications, including the synchronization of communication systems, electrical power grids, and financial networks. GNSS-derived time works well for any application where precise timing is needed by devices that are dispersed over a wide area. Seismic monitors that are synchronized with GNSS satellite clocks can be used to determine the epicentre of an earthquake by triangulation based on the exact time the earthquake was detected by each monitor [5].

9.0.9 Unmanned Vehicles

An unmanned vehicle is a vehicle that is unoccupied but under human control, whether radio-controlled or automatically guided by a GNSS-based application. There are many types of unmanned vehicles, including Unmanned Ground Vehicle (UGV), Unmanned Aerial Vehicle(UAV), Unmanned Surface Vehicle (USV), and Unmanned Underwater Vehicle (UUV).

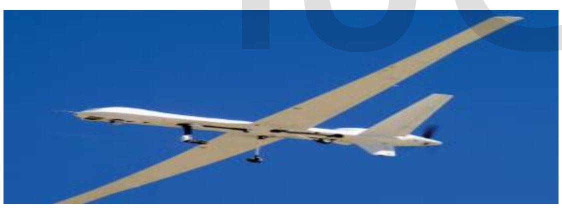

Figure 5: Predator Unmanned Aerial Vehicle (Source: ec-hobby.com)

Initially, unmanned vehicles were used primarily by the defence industry. However, as the unmanned vehicle market has grown and diversified, the commercial use of unmanned vehicles has also grown and diversified. Some of the current civilian uses for unmanned vehicles are search and rescue, crop monitoring, wildlife conservation, aerial photography, environmental research, infrastructure inspection, bathymetry, landmine detection and disposal, and disaster management. As the civilian unmanned vehicle market expands, so will the civilian use of unmanned vehicles [6].

9.0.10 Defence

GNSS technologies were initially designed mainly for defence applications before most of the systems were allowed for civilian use. In defence, GNSS is used for navigation which gives pilots and soldiers the ability to navigate unfamiliar terrains and even conduct night-time operations. Also, GNSS technologies have made SAR (Search and Rescue) operations possible and quicker to undertake. Various military formations also use GNSS to create maps of uncharted/enemy territories and also mark reconnaissance points. GNSS technologies are also used to guide unmanned vehicles which are used extensively in the military for various applications [5] and [11].

10.0 Conclusion

The space race which was part of the cold war between the Soviet Union and the United States led to the development of what we have as the GNSS now. It is a system that our ancestors can only dream of. In recent times, the general improvement in satellite systems such as GPS, GLONASS, and GALILEO and their interoperability has in several ways improved lives. Today, GNSS technology has drastically reduced human stress and save time as it has gained wide applications in several areas of human endeavour such as surveying, consumer market, transportation, machine control, precision Agriculture, construction, surface mining, time applications, unmanned vehicles, and defence.

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