FUTURE GLOBAL NAVIGATION SATELLITE SYSTEMS (GNSS)

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Abstract

Global Positioning System (GPS) has been widely used worldwide for a variety of applications such as air, land and sea. The GPS and the Russian GLONASS are the only fully operational Global Navigation Satellite System (GNSS). Due to its several advantages, such as simplicity of use, successful implementation and global availability, this has been considered as the cornerstone of positioning in navigation system applications for the people who are visually impaired. However, due to standalone single frequency service, the positioning performance has not been sufficient for some accuracy and precision demanding applications. The problems of obtaining high accuracy real time positions in the field have led the navigation community to develop a GNSS augmentation system. However, several questions have been raised with this new development, such as how good the new method is? During any satellite configuration, would it be able to provide the accuracy at the same level? In a reliable way, would it be able to replace conventional GPS method? In this paper, a detailed review of all necessary understandings concerning GNSS and with a focal point on the GPS, GLONASS, Galileo, Beidou and GNSS augmentation systems positioning performance, is provided. The enormous demand to further improve positioning, navigation, and timing capabilities for both civil and military users on existing GNSS systems has directed efforts to modernise the GPS and GLONASS system and introduce new systems such as Galileo navigation system.

Keywords: GPS, Galileo, GLONASS, Beidou, augmentation systems

Introduction

1.1 Modernised GNSS

The modernisation program aims at improving positioning and timing accuracy, signal availability and integrity monitoring support capability, and enhancement to control system. GNSS undergoes modification and a transformation process on a routine basis to provide better and sophisticated positioning services for the use of both civilian and military forces.

GPS was launched on a complete basis in 1995, with a constellation of 24 satellites. During the operation of GPS several generations of satellite have come up with improved features. In 2005, a major improvement to GPS infrastructure was made by disengaging old satellites and adding improved satellites. Another new mass of GPS satellites were launched, known as Block IIR-M satellites subsequently (Shaw, 2002; Hughes, 2005). In addition to the above improvements, a new positioning signal described as L2C was introduced meanwhile, but it has to undergo further improvisations before being opened for public use. Block IIR-M includes eight satellites, of these six of them were launched before March 2008. Hence, the total number of GPS satellites orbiting became 31 broadcasting satellites. Meanwhile another feature called the L5 safety-of-life civilian signal was initiated. The final satellite of this block series was effectively instigated in August 2009. By 2012, the civilian L5 signal would be accessible for consumers with the total launch of GPS IIF satellites. Block IIF is the final pushing step in the GPS block series that will highly modernise GPS process (GPS III) (DoD, 2015). This final phase will also consist of twelve new satellites, providing new military code (M-code) and civil signal frequency (L2C).

The Galileo and the Chinese Beidou systems will undoubtedly be practical, except these are not expected to be completely operational until 2017 and beyond 2020, respectively (de Selding, 2014). In contrast, the GLONASS system is currently being replenished and is fully functional with 24 satellites in operation.

At present GLONASS uses Frequency Division Multiple Access (FDMA) technology. During the modernisation plan, CDMA signals would be established at L1 and L5 frequencies near GPS and Galileo signals, starting with the GLONASS-K generation of satellites that has been launched in 2011. Beyond CDMA, signals would increase potential interoperability with the other CDMA-based systems in user equipment that would be able to process signals from satellites in multiple GNSS systems (Inside GNSS, 2011).

The present process of modernisation of GNSS will improve navigation user capabilities in various ways. There will be additional signals for civil use, which will be more powerful and easier to obtain by receivers. They will also facilitate interoperability between different systems (GPS, GLONASS and Galileo), by transmitting inter-system clock corrections (Gratton et al., 2010). There will be additional ground stations, and satellites will be able to communicate with each other, allowing better ephemeris generation, failure monitoring, and a faster alarm transmission in case a monitor triggers.

One of the predicted improvements is particularly significant to this work is the additional civil signal, and the ability to use a larger number of satellites in view at all times. This will translate into more precise accuracy; ionospheric delay is eliminated using dual frequency measurements, better availability and greater redundancy. In addition, smaller size dual frequency RTK receivers will allow GNSS to be used where DGPS is not practical, e.g. handheld navigation for the pedestrians and visually impaired people. DGPS positioning, which has a standard accuracy of 1-5m, will be mainly replaced by the RTK positioning, which will then offer a better accuracy.

The data rate requirements of DGPS will be decreased, in recognition of the modernisation. RTK applications that now use C/A-code and L1 and L2 carrier will take complete benefit from the supplementary L5-code and carrier and permit distances up to 100 km between the reference station and the rover, even when accuracies of few cm are targeted.

1.2 Galileo

Galileo is a system of navigation that is supposed to be Europe's independent and exclusive navigation system, offering better positioning services globally than standalone GPS. The European Union (EU) and the European Space agency (ESA), under civilian control were instrumental in launching this initiative. This global system would simultaneously co-operate with the existing GPS and/or GLONASS system, allowing users to gain from triple/hybrid satellite constellations services. This kind of availability of two or more collective satellite systems results in escalating the totality of available satellites in the sky. This will also help to augment the overall superiority of the positioning services even in urban areas and/or indoor environments. This will lead to a momentous boost in the number of navigation applications (Richard, 2008).

The central theme of the Galileo space segment is the global constellation of 30 operational satellites over an area of spaced orbital planes, and orbital inclination of 56º to the equator at about 23222 km above the Earth. Each plane comprises of eight satellites, supposedly 40º apart. For each plane there is a plan to keep two non-operational spare satellite, able to provide cover for any failed satellite in that plane. Thus, a breakdown or malfunction in the constellation can be fixed rapidly by substitution of the spare in place of the failed satellite. This can be time saving so that there is no need to wait for a new launch to be arranged, which can take several months and take up a lot of the productive time. The orbit altitude above Earth of 23222 km has been chosen to be appropriate; it would be convenient for the constellation to have a repeat cycle of 10 orbits in 17 days (Kaplan and Hegarty, 2006). The appropriate altitude of the satellites has to be in such a manner that gravitational resonances could be avoided. In this way, subsequent to primary orbit optimisation, station-keeping manoeuvres will not be required during the entire life span of a satellite. The altitude chosen also guarantees a high visibility of the satellites (ESA, 2007). By 2015, 18 satellites should be in place, followed by the rest in 2020. Initial services will be made available by the end of 2016 (ESA, 2015).

Satellite operations are supported by Galileo ground segment constructs of a network of ground stations, consisting of sensor stations, control centres and uplink stations. A worldwide network of Galileo Sensor Stations (GSS) will continuously monitor the satellites. The accurate measurements of the navigation signals will be sent to the two major Galileo ground segment. The Galileo ground segment in turn encloses two major control centres, the Ground Control Segment (GCS) and the Ground Mission Segment (GMS).

The Ground Control Segment (GCS) uses a global network of supposedly five Telemetry, Tracking and teleCommand (TT&C) stations to interact with each and every satellite on a plan combining regular, listed contacts, long-term test campaigns and emergency contacts. Data transference to and from the satellites, will be primarily performed through TT&C (Kaplan and Hegarty, 2006). TT&C network is comprised of five ground stations with 13 metre antennas working in the 2 GHz Space Operations frequency bands (S-band). A TT&C station network is mainly involved in overhauling of the Galileo satellite collection and giving access to global coverage. Nevertheless, general standard TTC modulation will permit the employment of non-ESA TTC stations when the navigation system of a satellite is not in process (during launch and early course operations or during a contingency).

The Ground Mission Segment (GMS) implements the functions for providing the main services of Galileo. Galileo Sensor Stations (GSS) supervises the navigation signals of each satellite on a daily basis. The data obtained with these sensor stations will be used for orbit determination, time synchronisation, and integrity monitoring.

The Galileo Sensor Stations (GSS) network will collect one-way pseudo-range raw measurements orientated to a local atomic reference clock with navigation messages received from the satellites. The Galileo Sensor Stations (GSS) network provides this data along with narrow meteorological and other data like monitor and control information and navigation data message to the Ground Control Centre (GCC) (Kaplan and Hegarty, 2006).

The integrity data computed at the Galileo Control Centre (GCC) will be made available to global users since they mainly use the dimensions from the worldwide network of sensor stations.

Galileo will afford 10 radio navigation signals allotted within the following frequency plans (Benedicto et al., 2000; Hein et al., 2001; Zimmermann et al., 2004):

- Four signals in the E5a and E5b bands (1164-1215 MHz), that includes two navigation data signals (the data channels) and two signals carrying no data (pilot channels).
- Three signals in the E6 band (1215-1300 MHz), and one split spectrum and one pair.
- Three signals in the E2-L1-E1, also described as L1 band (1559-1592 MHz), as well as one split spectrum and one pair.

A degree of optimisation is reached by using multiple signals in Galileo to fulfil the requirements of many kinds of applications that are accessed in diverse settings and circumstances, such as indoor, outdoor, static and rapid moving. This is presently unavailable in GPS because only one civilian signal is available and accessible. But this problem would be overcome in the subsequent sophistication of GPS. A particular advantage of having multiple signals in the ionosphere layer is that after adding measurements obtained from at least two different signals, it is possible to cancel the ionospheric delay.

The Galileo navigation signals offer the following advantages to the end users (Benedicto et al., 2000; Hein et al., 2001):

- Open Service (OS).
- Safety-of-Life Service (SoL).
- Commercial Service (CS).
- Public Regulated Service (PRS).
- Search and Rescue (SAR) Service.

Generally, the Open Service (OS) data signals are allocated at E5a, E5b, E2-L1-E1 (L1) bands for either data or pilot channels allowing several signal combinations for the single and dual frequency positioning services. The bottom line of the single frequency OS is that they use signals which are in E2-L1-E1 and might receive the GPS C/A code signal on L1. For enhanced precision, signals in E5a and E5b bands might also be incorporated. The GPS L5 signal is included in dual frequency services. The data carried by the OS signals are not in an encrypted form and are usable for all. The OS service does not offer integrity information, and no signal quality determination is assured to the user.

The safety-of-life (SoL) service relies on the data contained in the OS signals and also uses reliability data carried in a special channel. The Commercial Service (CS) is based on two supplementary signals within the E6 frequency band and the capability of using the OS signals. This pair of signals is in encrypted form offering higher performance for commercial users only. The Public Regulated Service (PRS) operates at all times, even during emergencies, and will be used by governmental authorities such as the police, coast-guards and customs, etc. For this service two additional signals are also allocated, one in E6 band, and the other in the L1 band. These signals are encrypted in order to have access control, so access is restricted to PRS users.

1.3 GLONASS (GLObal'naya NAvigatsionnaya Sputnikovaya Sistema)

The GLONASS satellite system is currently under development with new modernised GLONASS spacecraft to replenish the constellation. The GLONASS have currently 28 satellites in orbit, 24 operational (IAC, 2015). The GLONASS system and GPS systems share similar principles in data transmission and positioning methods. The difference between GLONASS and GPS is the segment; GLONASS consists of 24 satellites (21 active and 3 spares) in three orbital planes. The three orbital planes are separated by 120º and the satellites within the same orbit plane by 45º. Each GLONASS satellite operates in circular 19100 km orbits referenced to the Earth’s surface with an inclination angle of 64.8º and each satellite completes an orbit in approximately 11 hours and 15 minutes. Two L-band navigation signals are transmitted by the satellites and the Russians are planning to develop and add a third L-band signal near the radio frequency of the new L5 signal planned for GPS (Kaplan and Hegarty, 2006). GLONASS offers two types of services: Standard Positioning (SP) and High Precision navigation signal (HP). SP service offered world-wide with horizontal accuracy of 57-70 meters, the vertical accuracy is within 70 meters.

The Russian government has stated that, like GPS, GLONASS is a dual use system and that there will be no direct user fees for civil users. The Russians are working with the EU and the United States to achieve compatibility between GLONASS and Galileo, and Galileo and GPS, respectively (Kaplan and Hegarty, 2006). The functions of the ground control segment of GLONASS are entirely located within former Soviet Union. The ground control centre and time standards are located in Moscow. At various locations across the continent, observations of telemetry data and ranges are made and passed to ground control centre in Moscow. The control information and ephemerides are computed and uploaded to satellites. At least five satellites will be available at any location, at any time worldwide under the full constellation (Miller, 2000).

With 24 satellites currently operational (at time of writing), GLONASS does not work well as an independent positioning solution for high accuracy applications. However, if it is used as a supplement to GPS and the RTK, GLONASS does provide more reliability, availability, accuracy and more satellites in view throughout the day. The additional GLONASS visibility is often enough to overcome suburban environments or mountainous areas and the standard down times when using GPS-only for RTK.

Nevertheless, the amount of GPS and GLONASS satellites that can be observed is still often rather unsatisfactory for the attainment of a position solution. This is partly due to the requirements of at least five visible satellites to determine a position because of an offset between the timescales of GPS and GLONASS to be resolved (Cai and Gao, 2009).

1.4 BeiDou Navigation Satellite System (BDS)

The Chinese BeiDou system is a multistage satellite navigation program designed to provide positioning, fleet-management, and precision-time broadcasting to Chinese military and civil users. The BeiDou satellite system is developed by China Academy of Space Technology (CAST). Unlike the GPS, GLONASS, and Galileo systems, which use medium Earth orbit satellites, BeiDou satellite system uses satellites in geostationary orbit over China. Currently BeiDou satellite system is in a semi operational phase, with 17 satellites deployed and it is expected to provide global navigation services by 2020. China's Beidou Navigation Satellite system provided services for China and its surrounding area since the year 2000, and provided services for most part of Asia-Pacific areas by the end of 2012. (BeiDou Navigation Satellite Sysytem, 2015). The BeiDou satellite system provides a radio determination satellite service, unlike GPS, GLONASS, and Galileo, which employ one way TOA measurements. The radio determination satellite service requires two way range measurements. The system engages a ground based control centre sending an interrogation signal through one of the BeiDou satellites to a user's ground based navigation receiver, with the receiver then transmitting back a response through at least two of the system's three geostationary satellites.

The central station receives the responding signals sent by the user from at least two satellites, and calculates the user's 2D position based on the time difference between the two signals. With this time lapse information, the known locations of the two satellites, and an estimate of the user altitude, the user's location can be determined by the operations centre (BeiDou Navigation Satellite Sysytem, 2015). Once calculated, the position is then compared with the digital territorial map stored in the database to get the 3D position data, which is then sent back to the user via satellites using encrypted communications. Since the BeiDou system requires dual-way transmissions, the BeiDou receivers are generally bigger, heavier and more expensive compared to GPS / GLONASS user receivers.

2. Gnss augmentation systems positioning performances

A number of navigation applications have used augmentation and complementary systems for the purpose of achieving enhanced positioning performance. Various researchers have carried out the evaluation of such systems under different conditions and scenarios. The following section presents different evaluation studies, as well as the reported results of positioning performances, taking one main augmentation system into account: the use of network-based DGPS.

2. 1 Network-based DGPS

A number of regional DGPS networks are functioning worldwide, providing pseudo-ranges corrections estimation based on multi-reference DGPS stations being unified together forming a WADGPS solution. There are many advantages associated with network-based DGPS compared to the standard single-reference DGPS station approach. Several advantages are the advanced reliability of the differential positioning service, increased strength, and higher positioning accuracy levels. These advantages can be achieved for code-based DGPS and RTK measurements (Lachapelle et al., 2000; Park et al., 2003; Raman and Garin, 2004; Oh et al., 2005).

Chang and Lin (1999) described a local navigation system consisting of a medium-range DGPS network developed in Taiwan. The objective of this network was to provide adequate positioning accuracy using GPS observations based on C/A pseudo-ranges collected from a set of reference stations and then processed at the central station obtaining a weighted average of the differential corrections. The developed medium-range DGPS based positioning service has achieved an improvement of 35% in terms of Root Mean Square (RMS) error comparing to the single reference station as shown by the testing results. The use of single reference-based DGPS was very much dependent on the baseline lengths; the horizontal accuracy ranged from 3.1 to 5 meters. However, when utilising three reference stations, these measurements, provided an average of 1.3 meters' accuracy. These were achieved only in static scenario without a hint to the surrounding environment.

The Jet Propulsion Laboratory (JPL) of the National Aeronautics Space Administration (NASA) launched Internet-based Global Differential GPS (IGDG) in spring 2001. A subset of 40 reference stations is available at NASA's Global GPS Network (GGN). These reference satellites allow real-time streaming of data to a processing centre, that determines and subsequently distributes accurate satellite orbits and clocks errors, as global differential corrections to the GPS broadcast ephemerides (as contained in the GPS navigation message) over the open internet. This process could be done on a real time basis. An introduction to IGDG can be found in

Mullerschon et al. (2001a) and on IGDG (2004). Technical details in Bar-Sever et al. 2001; Mullerschon et al., 2001b.

The low bandwidth correction data stream can be downloaded into a computer by the internet users. It will then be combined with raw data from the user's GPS receiver. The user's GPS receiver must be a dual frequency and be of geodetic quality so as to extract the full potential from the accurate corrections. The ultimate, but decisive, constituent that offers an end-to-end positioning and orbit determination capability is the navigation software possessed by the user.

Raman and Garin (2005) assessed the performance of the Global Differential GPS (GDGPS) system, provided by JPL, for particular specific frequency C/A GPS receiver. This system makes use of a group of DGPS reference stations which are continuously observing GPS measurements. The NTRIP protocol would be utilised to measure the central processing stations and then to forward the improvement messages to the users. At the processing stations, data is analysed to produce measurement corrections of ionospheric delay and satellite state (orbit + clock corrections). The corrections are then provided as an information vector reliant on the user's location. The improvements in terms of horizontal position accuracy using GDGPS augmentation services were measured in open space conditions. A horizontal accuracy average of 1.5 meters using GDGPS was achieved in comparison to 4 meters using standards local DGPS. Nonetheless, these accuracy levels were decreasing within the distance from the reference stations and when the availability of corrections was reduced at the user side. A linear combination algorithm was also developed by Oh et al. (2005) in order to generate interpolated Pseudo-Range Corrections (PRC), which was the used to enhance the DGPS positioning accuracy. The combination algorithm takes into consideration PRC values from multiple DGPS reference stations sharing the same satellites. The accomplished DGPS positioning accuracy was improved over standard DGPS by 40% in static scenarios. When using PRC measurements from two DGPS stations a position accuracy of 1.8 meters was achieved, and around 1.5 meters when using three or more DGPS reference stations.

2.2 GNSS Augmentation Systems in Pedestrian Applications

When taking the performance of GNSS and its augmentation methods of pedestrian users into account, in densely urban and indoor environments, a pedestrian navigation project was defined and described by Abwerzger et al. (2004) and Ott et al. (2005). This project was named "Definition and Demonstration of Special Handheld based Applications in Difficult Environment" (SHADE), and was supported by the European Space Agency (ESA) in order to explore different sets of navigation technologies employed for pedestrian applications in difficult environments. Three autonomous navigation prototypes were developed and tested in the SHADE project. The first prototype was formed of an A-GPS received, EGNOS[1] functionality included. The second prototype was composed of and INS[2] module, for the sake of pedestrians (a dead reckoning module), as well as GPS/EGNOS receiver. The last prototype was encapsulated of an Integrated GPS/Loran-C with EGNOS facility. The Long Range Aid to Navigation (LORAN) is terrestrial radio navigation system utilising low frequency radio transmitters. The present development of this technology is presented as Enhanced LORAN (E-LORAN) (Abwerzger &Lechner, 2002; Narins et al., 2004). The operational architecture of SHADE was designed to evaluate and develop the availability of several positioning solutions to operate even in dense urban and indoor environments. Field measurements were carried out under good GPS visibility conditions, during the evaluation of the first prototype, and then under light in-doors (partly covered areas) with a sampling rate of one sample per second. An accuracy of 1.5 meters at 95% was achieved in open space areas when using the first prototype. The worst scenario was noticeable during indoor measurements, in which the achieved accuracy reached 39.22 m at a 95% confidence level. This positioning performance is considered four times higher than GPS SPS horizontal levels (7.8-12.8 m) described by Hughes (2005). Hence, the conclusions were that the first prototype is not suitable for navigation applications taking place indoors. In addition, the second prototype was evaluated permitting position determination to take place in GPS complicated environments, in which a primarily absolute position was determined by the GPS/EGNOS receiver, and constant position samples were compromised from the dead reckoning module as well as the GPS/ENOS receiver using Kalman filtering. However, one of the central drawbacks of the second prototype was the position drift because of the attached magnetometer. The third prototype has made known its capacity to increase the availability of position solutions and surmount the blockage of GPS service in densely urban area. On the other hand, the position solution's accuracy, obtained from the integrated Loran-C service, was lower than the expectations. Furthermore, upon entering the buildings, the signal strength from all Loran-C stations decreased considerably. Thus, the Loran-C was no longer regarded as reliable.

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[1] European Geostationary Navigation Overlay Service (EGNOS) is a satellite based augmentation system (SBAS) under development by the European Space Agency, the European Commission and EUROCONTROL. The primary goal of EGNOS is to provide augmentation service for GPS, GLONASS and the future Galileo system.

[2] Inertial Navigation System (INS) is a navigation facility that comprises several motion and orientation sensors (e.g. accelerometers and compasses) which are integrated using a computer application to sense and continuously calculate the position, speed and time.

3. Summary

This paper presented a detailed review of Global Navigation Satellite System (GNSS), such as GPS, GLONASS and Galileo, along with its most widely implemented augmentation technologies such as DGPS and network-based DGPS was presented. Additionally, recent augmentation systems evaluation studies conducted by previous researchers were reviewed, showing the achieved positioning performance. The positioning performance of GPS is affected by the capability and productivity of the linked augmentation systems, at present as result of higher efficiency standards and better coverage competence, the WADGPS systems like the network-based DGPS are the augmentation systems which are mainly successful. However, this positioning performance is based on the availability of up-to-date corrections, which is affected by the data deliverability means, measurement scenario and navigation environments. However, still the positioning performance achieved from GPS augmentation system is considered not sufficient for these applications. Network-based DGPS and DGNSS techniques have still not been looked at and made use of for the aid of utilising GNSS system in significant pedestrian applications.

The analysis of the available methods to support the mobility of visually impaired people also includes the descriptions of technologies employed in the methods, including the GNSS and the augmentation technologies.

The information provided in this paper provides the state-of-the art in GNSS and the augmentations technologies.

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