GNSS principles and comparison

Safaa Dawoud
Potsdam University
Potsdam, Germany
Email: sdawoud@uni-potsdam.de

***Abstract*—Over the past years, there has been an increase in number of Global Navigation Satellite Systems (GNSSs). Some of these GNSS are already in service, but some of them still under development. As a result of developing these systems by different countries spread through different continents, users will soon be overwhelmed by lists of concepts, features, and idioms, which are announced by different competing systems.**

The purpose of this paper is to review main principle of any GNSS then to compare different GNSSs including GPS, GLONASS, Galileo, and Compass. However, in this paper, we focus more on GPS system as it is the only GNSS that is presently at a full operational capability and widely used in the last ten years.

I. INTRODUCTION

GNSS is used to determine the position of a receiver on land, at sea, or in space by means of constellation of multiple artificial satellites. Determining receiver position (i.e. latitude, longitude, and height) relies on calculated distance to several satellites. Each satellite continuously broadcasts a navigation message. The receiver uses the received message, from satellites in the view, to determine the transit time of each message and compute the distance to each satellite.

Constellation with a sufficient number of satellites must be launched for each GNSS to ensure that at least four satellites are simultaneously visible from any point on Earth. The satellite is able to stay in a stable orbit due to gravity force, which is sufficient to accelerate the satellite in its orbit. Fuel energy is only used to move the satellite to another orbit or to maintain the satellite in its correct orbit in case of deviation caused by external object gravity (i.e. Moons and Suns gravity). Solar panels are used to power all electronics and radio receivers and transmitters on board. Each satellite covers a range; each range defines a surface of sphere, where the satellite is in the center of this sphere.

Typically, three satellites are enough to determine longitude, latitude and height from the three sphere equations. The satellites have atomic clocks which can be synchronized to the level of nanosecond, but this is not the case with current receivers, as the atomic clocks are expensive (i.e., more than $100,000 each). Therefore, receivers' manufactures use inexpensive crystal clocks. However, one µs synchronization error leads to a position error of 300 meters. To overcome the synchronization problem, a fourth satellite signal will be needed to calculate Δt. Mathematically, to solve four unknowns (i.e., x,y,z and Δt), there must be four equations. As a matter of fact, using more satellites not only allows Δt calculation, but also increases the accuracy of the receivers' position calculation.

The past decade has seen a rapid development of several GNSSs. Some of them are already in service (e.g. GPS by USA). However, some GNSSs still under planning or partial operational phase (e.g., Compass by China and Galileo by European Union). Moreover, GLONASS struggled for many years until being back to full service lately at 2011. In this paper we overview the principles of GNSS depending on GPS but also compare the other GNSS systems. Section II starts with a brief introduction to GNSS, then it is followed in section III by intensive details about GPS. Sections IV and V study in detail GLONASS and Galileo systems respectively. Section VI shows the revealed information about other GNSSs that are under development. Section VII is a comparison between GPS, GLONASS, Galileo, and Compass systems. Finally, section VIII concludes this paper and shows how the growth in the number of GNSSs could be turned into an advantage.

II. GNSS CONSTELLATION AND SEGMENTS

GNSS systems should have a constellation with sufficient number of satellites launched to ensure that at least four satellites are simultaneously visible at every site. The GNSS satellites have atomic clocks, radio transceivers, computers and supporting equipments used for operating the system. The signals of each satellite allow the user to measure an approximate distance from the receiver to the satellite, which is called the pseudorange. The pseudorange is calculated from the signals time of travel from a satellite to the receiver. Since radio signals are traveling at the speed of light c, where $c = 299,792,458$ m/s.

pseudorange = (time difference) $\times$ c

GNSS usually consists of three segments: space segment, control segment, and user segment [1].

Space segment consists of many satellites that are placed above the Earth in nearly circular orbital planes. There are three different Orbit altitude, low earth orbit (LEO), medium earth orbit (MEO), and geostationary earth orbit (GEO) satellites. The relation between orbit altitude and Earth circulation period are fixed. LEO satellite are located at an altitude of under $2,000$ km and circulate the Earth in the range of 95 to 120 min. MEO satellites are located at an altitude of $5,000$ to $12,000$ km and take around 6 h to circulate the Earth. The altitude of GEO satellites is fixed at altitude of $35,786$ km, in which they exactly match the earth rotation speed (i.e., circulate the earth once in 24 hours) and remain exactly at the same point from the earth view. Each satellite is equipped with devices that are used for navigation or other special tasks. The satellite receives, stores, and processes transmitted information from a ground control center. To identify each satellite, the satellites have various identification systems (i.e., the launched sequence number, the orbital position number, and the system specific name).

Control segment is responsible for controlling the whole system including the deployment and maintenance of the system, tracking of the satellites in their orbits and the clock parameters, monitoring of auxiliary data, and upload of the data message to the satellites. The control segment is also responsible for data encryption and service protection against unauthorized users. Moreover, tracking stations located around the world coordinate the activities for controlling and monitoring the system using bidirectional communication between these stations and GNSS satellites.

User segment consists of passive receivers able to decode received signals from satellites. Using these receivers is not associated with any fees. However, civilians are not allowed to access GNSS military signals. Therefore, besides the special receivers designed for military applications, there is a diversity of GNSS receivers available on the market today.

III. GPS SYSTEM

The US Department of Defense (DoD) started to develop a global positioning system since 1973 for military purpose, the first satellite was launched in 1977. DoD's NAVSTAR Global Positioning System (GPS) reached the full military operational capacity in 1995. The US congress took actions to make the global positioning service available for civilians in 2000, since that time DoD is offering unlimited access of GPS service to the civilians in all over the world free of charge.

A. GPS constellation and segments

The space segment of GPS systemconsists of 24 active satellites, which are placed in MEO at an altitude of 20,200 km above the earth. The satellites are spaced in orbits to ensure that at any point of time there are at minimum 6 satellites in the receiver view. Currently there are 31 operational GPS satellites were launched in the space by the US Air force plus 3 to 4 inactive satellites that can be reactivated when it is needed [2]. Each satellite transmits radio signals that travel at the speed of light to broadcast the navigation massages. The control segment consists of a network of monitoring stations that are responsible for satellites' tracking, monitoring, and maintenance. The master control station, located in the state of Colorado, gets data from each of the monitoring stations, which are distributed around the world, and determines both the data to be uploaded and the ground stations that will transmit this control data to the satellites.

The user segment consists of handset radio receivers that receive signals from GPS satellites available in the view. Actually, there are millions of receivers in use today. These devices include 300 million receivers in cell phone [3].

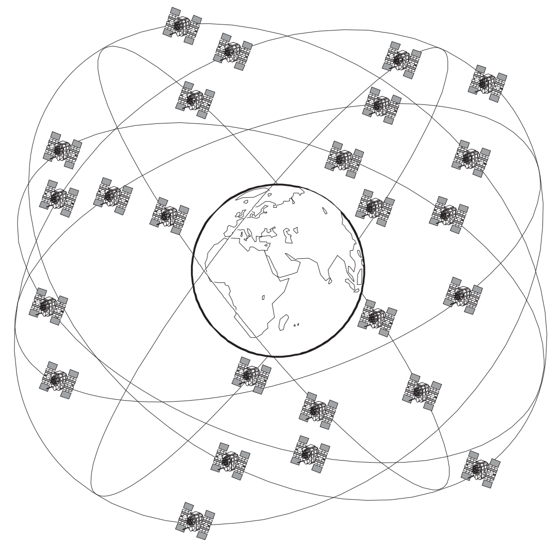


Fig. 1. GPS satellites

B. GPS Signals and Navigation Message

Signals are transmitted to the user segment at frequencies $L1 = 1575.42$ MHz, and $L2 = 1227.60$ MHz. These two carriers $L1$ and $L2$ were selected to ensure that the signal is robust as possible against ionospheric effects and weather conditions. They are generated as multiples of the fundamental satellites clocks frequency (i.e., $f_0 = 10.23$ MHz) [4]. The satellites transmit L1 and L2 signals to the user, which are encoded with information on their clock times and their positions. Both the civilians and USA military can access L1. However, L2 is only accessible by US government and military, as it carries encrypted signals in which only the military and US government receivers can decoded. There are two types of codes on the carrier signals: Coarse acquisition code (C/A) code and precise (P) code. The C/A code is modulated on the L1 carrier. The L1 carrier can transmit the C/A code at 1.023 chips and repeats the code sequence every 1ms, while the required bandwidth is 1 MHz. This chipping rate means that a single chip has a length of 300 m and that the entire C/A codes repeat themselves every 300 km during transmission [4]. The C/A code contains the time information according to the satellite atomic clock when the signal was transmitted. Each satellite has a different C/A code, so that they can be uniquely identified. The P (precise) code is modulated on both the L1 and L2 carriers. The P code is more precise than the C/A code. The P code is a very long code consisting of approximately 1014 chips. The L1 and L2 carriers can transmit the P code with a chip rate 10.23 MHZ, which means that the resolution of P code is ten times higher than C/A code. The P code repeats every 38 weeks. The carrier can transmit the P code at 10.23 Mbps with a chip length of 29.3 meters. The P code also contains the time information according to the satellite atomic clock when the signal was transmitted same as C/A code, except that it has a resolution of ten times C/A code has, also the P code can be encrypted by a process known as anti-spoofing.

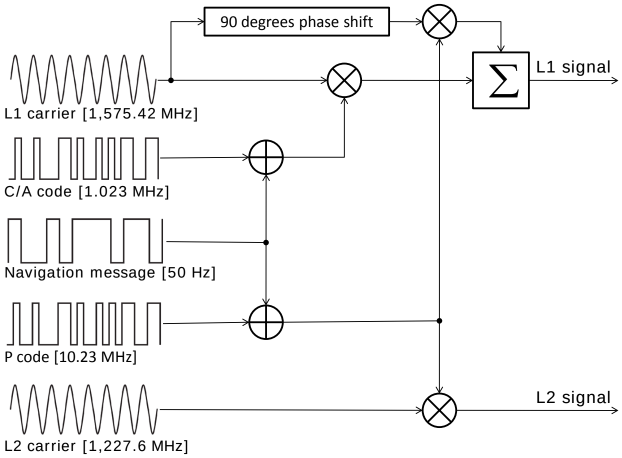


Fig. 2. Pilot signals and codes

The frequency of $L5$ is 1176.45 MHz, with chipping rate of 10.23 MHz similar to P code. The high chipping rate of L5 code provides high performance ranging capabilities and better code measurement than L1 C/A code measurements. It is exclusively reserved for safety of life transportation and other high performance applications.

The Navigation Message is encoded onto the signal in the L1 carrier. It is transmitted at a very low rate of 50 bps. It consists of frame with a 1500 bit sequence and it is mixed with the C/A code, therefore the entire frame takes 30 seconds to be transmitted. Each frame consists of five subframes, each with length of 30 bits. Each subframe starts with a telemetry and a handover word (TLM and HOW) used to indicate the beginning of a new subframe. Moreover, (TLM and HOW) are also used for synchronization purpose. The first subframe contains 10 bit for the current GPS week number (every 1024 weeks the week number restarts at 0), the satellite state and health (e.g. navigation data corruption), the clock correction data, which is about the drift of the satellite clock with respect to GPS time [5]. The satellites clocks are monitored continuously by the ground stations and send the data to the master control station, the master control station compute the clock correction and upload it to each satellite.

The second and third subframes contains the ephemeris data of the satellite, they provide the needed information about the exact satellite position in the orbit. The fourth and the fifth subframe contains the almanac data and health data for all satellites in the GPS system, also the difference between GPS and Coordinated Universal Time(UTC) and information for computing the delay caused by the ionosphere.

The size of the alamanc data about all GPS satellites doesn't fit in only two subframes (i.e., the fourth and the fifths subframes). In GPS systems these data are transmitted over 25 frames, these 25 frames referred to one master frame, where the first, second, and third frame are repeated in each frame, the fourth and fifths subframes are carrying a different parts of the almanac data of all GPS satellites. The masterframe will take 12.5 minutes until the receiver receive all the related 25 frames.

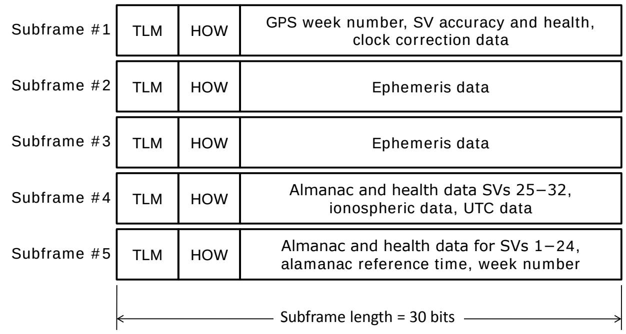


Fig. 3. GPS navigation message: frame structure

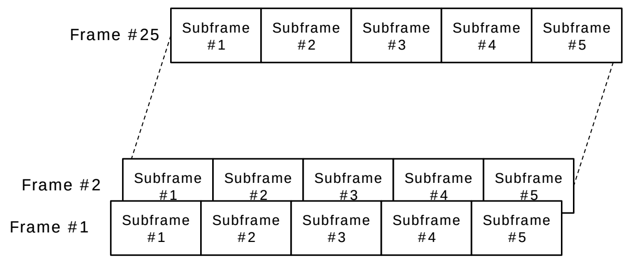


Fig. 4. GPS navigation message: masterframe structure.

C. GPS positioning

GPS positioning is based on trilateration method, which is a mathematical calculations to find out the position of something by knowing its distance from a number of known points. In reality a position has to be determined in three dimensional space, so 3D trilateration requires to know 3 points lie on the surfaces of three spheres to determine the position, which coordinates (X, Y, Z). In GPS systems, the receiver requires to determine four ranges (surface of sphere) of four satellites, three for calculating the position in 3D and the fourth one for time synchronization to correct receiver clock error.

The first step for the receiver to determine its position is to determine which satellites to be used in the measurements depending on: First, the geometry between each satellite and the receiver. Second, the satellite signal state and health, which determines whether the navigation data is corrupted or not. The receiver should select at least four satellites, in which three satellites are needed to calculate the position in 3D, i.e. (X, Y, Z), in addition a fourth satellite is needed to calculate the fourth parameter, which is Δt to overcome the synchronization problem that caused by the receiver clock error. Then the receiver needs to determine the pseudorange for each satellite. The pseudorange p_i deviates from the real range r_i by error ϵ due to the ionosphere refraction, the receiver clock error, and the multipath propagation. The receiver uses the correction formula sent by the satellites to overcome these errors and applies it in the measured ranges to reach accurate results.

$$r_i = p_i + \epsilon \quad (1)$$

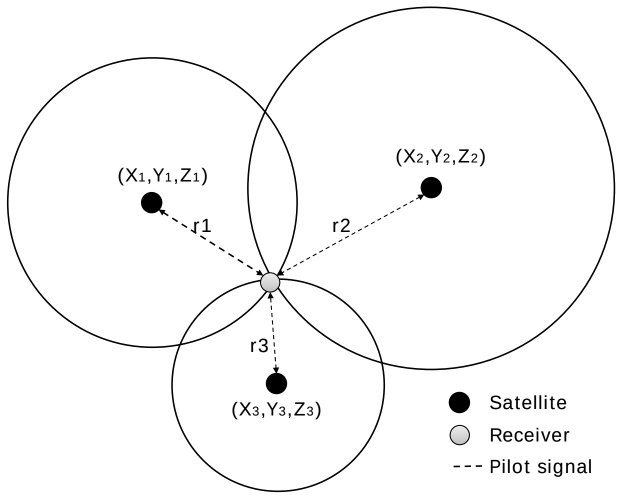


Fig. 5. Circuler lateration

After defining the satellites ranges, the receiver needs to define the known position vector for each satellite i as $r_i = [X_i, Y_i, Z_i]^T$ using the orbit parameters included in the received navigation message, and calculate the unknown receiver position vector $r_u = [x\ y\ z]^T$ using the corrected pseudorange p_i and the calculated Cartesian coordinates (X_i, Y_i, Z_i) for each satellite i as in equation 2, where c is the velocity of light, and Δt is the time offset between the receiver clock and GPS time.

$$p_i = \sqrt{((X_i - x)^2 + (Y_i - y)^2 + (Z_i - z)^2)} + c.\Delta t \quad (2)$$

From equation 2, the receiver position is given in Cartesian coordinates. These Cartesian coordinates are transformed to geodetic coordinates; the geodetic system presents the location on the earth by its latitude, longitude and height. The currently used geodetic system by GPS called WGS-84. WGS-84 is a model of ellipsoid representing the earth that is used by the receivers in transforming the Cartesian coordinates of the satellite position to the geodetic coordinate [6].

D. Location Accuracy

There are different factors that affect the accuracy of GPS measuring. The major sources of errors are shown in table I.

Ionosphere: The ionosphere is the upper most part of the atmosphere from a height of about 50 km to more than $1,000$ km. The ionosphere is a dispersive medium. During GPS signals transmission through the ionosphere in its way to the earth, it is dispersed by the free electrons that are in the ionosphere. It is difficult to estimate the ionospheric effects, as the ionosphere varies significantly from day to day and within the same day due to the physical interactions with solar conditions. The ionosphere delay can cause error starts from few meters to more than 20 m. However, the largest errors were recorded during solar storms [3]. The ionospheric effect is more significant for the satellites lower to the horizon. The receivers ignore the signals from the satellites that are below a certain angle from the position calculation, and use what called ionospheric model, which eliminates the ionospheric error by using a linear combination of dual frequencies (L1 and L2) or triple frequencies introduced with the availability of the new L5 signal to measure the ionospheric effects.

TABLE I
TABLE MAJOR SOURCES OF RANGE ERROR

Error Source	Error Magnitude
Ionosphere	7 meters
Troposphere	0.6 meters
Ephemeris error	2-3 meters
Satellite clock error	1-2 meters
Multipath	1-2 meters (highly dependent on environment)
Receiver noise	1-2 meter

Troposphere: The troposphere is the atmosphere layer that starts from the earth surface to the height of about 50 km. It is not frequency dependent. The GPS signals are affected by the neutral atoms and molecules in the troposphere. Tropospheric models estimate the tropospheric delay due to the values of the temperature, pressure, and humidity.

The orbital error: The satellites are positioned in precise orbits; a deviation from these orbits could happen due to gravitation forces. To overcome the orbit data error the satellites positions are monitored and controlled regularly and the corrected data are included in the ephemeris data, which are broadcasted within the navigation message

Satellite clock error: The GPS satellite clock bias, drift and drift-rate are explicitly determined by the master control station Colorado Springs that monitors the behavior of the satellites clocks. These parameters are broadcasted in the navigation message.

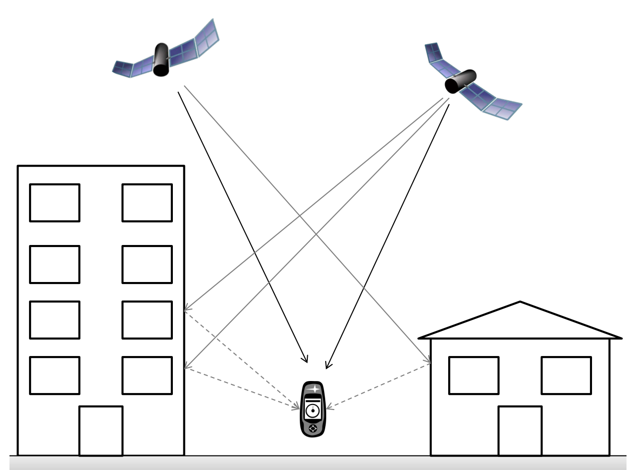
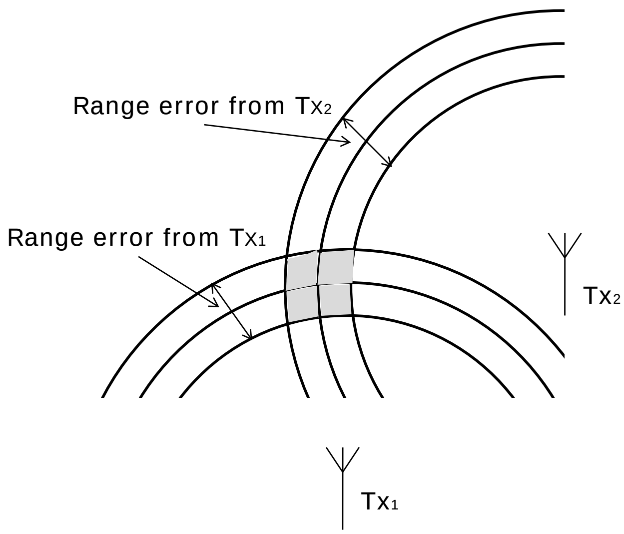


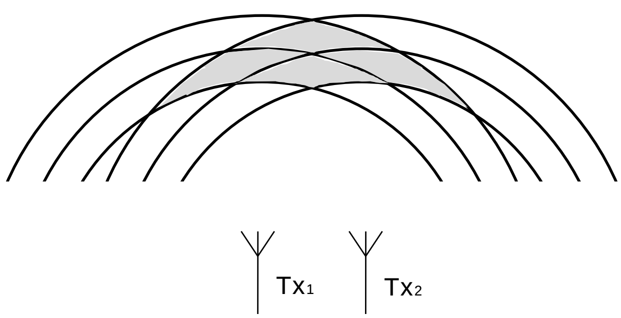
Fig. 6. Interference caused by reflection of the signals

Multipath propagation: The multipath taken by the signal to arrive to the destination is caused by reflection of satellite signal on objects (buildings, trees, etc...). The reflected signal takes more time to reach the receiver than the direct signal, as seen in figure 6. Various methods used to reduce the multipath effect as antenna based mitigation and improved receiver technology [7].

Satellites geometry: The satellites geometry is one of the major factors that affect the location accuracy. When the satellites are allocated close to each other, the area of overlap of the signals is larger, which means that the area of uncertainty is larger. Figure 7 shows the two cases: First, as in figure 7(a) the satellites are spread; in this case the area of uncertainty is relatively small. Second, as in figure 7(b), the uncertainty area has become larger because the satellites are close to each other.



(a) Uncertainty area for well distributed transmitters



(b) Uncertainty area for collocated transmitters

Fig. 7. Effect of DOP

The effect of satellites geometry is usually expressed by the Geometric Dilution of Precision (GDOP) factor. The Dilution of Precision (DOP) is the ratio of the positioning accuracy to the measurement accuracy. It is usually greater than unity, however, if many satellites are observed (e.g. more than 8) the value of DOP can be less than unity [8].

Based on which factors are used for the calculation of the DOP values, different variants are distinguished:

1) GDOP (Geometric Dilution Of Precision); Overall-accuracy; 3D-coordinates and time
2) PDOP (Positional Dilution Of Precision) ; Position accuracy; 3D-coordinates
3) HDOP (Horizontal Dilution Of Precision); horizontal accuracy; 2D-coordinates
4) VDOP (Vertical Dilution Of Precision); vertical accuracy; height
5) TDOP (Time Dilution Of Precision); time accuracy; time

In the case of GPS point positioning, which requires the estimation of 3-D position and receiver clock error, the most appropriate DOP factor is GDOP [8]:

$$GDOP = \sqrt{PDOP^2 + TDOP^2} \tag{3}$$

More information on calculating DOP is in [4].

E. Differential GPS

Differential techniques have been developed for high accuracy applications such as flights landing systems. It handles the errors that are unique to each receiver due to its current local region, such as signal path delays through the atmosphere, in addition the satellite clock and ephemeris, receiver measurement noise and multipath propagation and other error sources. The user receiver (UR) can calculate his accurate location by using differential corrections provided by the GPS reference receiver (RR) that is in the local region. The RR is allocated at accurately known allocation to measure the GPS errors, which equipped with accurate receiver technology.

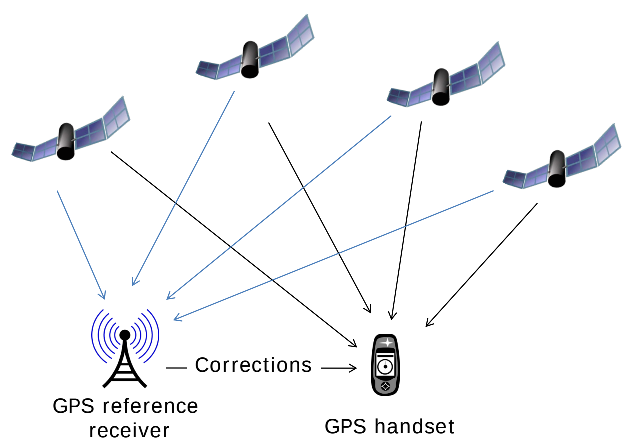


Fig. 8. Differential-GPS architecture

A simplified DGPS architecture is shown in figure 8. RR is located at an accurately surveyed location. The RR receives signals from all GPS satellites in the view and calculates the two ranges $r_{i,rs}$ and $p_{i,rs}$, where $r_{i,rs}$ is the true range. According to equation 4, $r_{i,rs}$ is the range between the accurate position (x_{rs}, y_{rs}, z_{rs}) of the RR and the position (X_i, Y_i, Z_i) of the ith satellite, which is provided in the ephemeris data in the navigation message.

$$r_{i,rs} = \sqrt{(X_i - x_{rs})^2 + (Y_i - y_{rs})^2 + (Z_i - z_{rs})^2} \tag{4}$$

While $p_{i,rs}$ is the measured pseudorange, which differs from the true range $r_{i,rs}$ due to significant errors mentioned earlier.

$$p_{i,rs} = r_{i,rs} + c \times \Delta t_{i,rs} + \epsilon_{i,rs} \quad (5)$$

where $\Delta t_{i,rs}$ is the time offset and $\epsilon_{i,rs}$ is the range difference caused by error sources.

The RR then calculates the distance between $r_{i,rs}$ and $p_{i,rs}$ for each visible satellite and composes a set of correction

$$\Delta p_i = p_{i,rs} - r_{i,rs} = c \times \Delta t_{i,rs} \quad (6)$$

data, which is broadcasted as a radio signals or cellular networks. The UR selects a set of satellites for which correction data is available to calculate its current position.

$$p_{i,mr} - \Delta p_i = r_{i,mr} + c \times \Delta t_{i,mr} + \epsilon_{i,mr} - (c \times \Delta t_{i,rs} + \epsilon_{i,rs}) \quad (7)$$

The accuracy of DGPS degrades as the distance from the RR increases. For high level of accuracy the UR needs to be within 100 km of the RR that provides the corrections [3]. Since the ranges observed by the RR and a UR Within this distance usually experience tropospheric, ionospheric, multipath, and noise errors of similar magnitude[4].

IV. GLONASS

The GLONASS (Global'naya Navigatsionnaya Sputnikowaya Sistema) system is developed and managed by Russian Federal Space Agency and Ministry of Defense in 1970. The Union of Soviet Socialist Republics started the development of GLONASS based on their experience with Doppler satellites system Tsikada.

The first GLONASS satellite were launched and successfully deployed in 1984, till 1993 the orbital constellation of GLONASS reached 12 satellites. In 1996, GLONASS became fully operational with completed constellation of 24 satellites. Between 1996 and 1998, the number of available satellites was decreasing due to the financial support. In 2001, the number of available satellites was only 6 to 8 satellites [1].

After 2000, the Russian economy recovered and the GLONASS system becomes one of the top priorities of the president. Since that time, a plan was set to restore a full operational capability of GLONASS system in 2009. However, there was a delay in the plan due to some complication and failures to launch the needed satellites. In December 2010 the Russian space agency failed to send three GLONASS navigation satellites into orbit; they have fallen into the Pacific Ocean. Until December 2011, they announced that the GLONASS constellation has reached the number of 24 operating satellites in the orbit after launching the 24th satellite from Baikonur Space Center at November 2011 [9].

GLONASS was developed mainly for military purpose. However, after the full operation capability was achieved, the GLONASS becomes available free of charges for civilian usage.

GLONASS coordinates were expressed using Soviet Geodetic System 1985 (SGS-85). In 1994, the GLONASS coordinate reference system changed to SGS-90. SGS-90 is known these days as ParametryZemli 1990 (PZ90) or PE-90 (Parameters of the Earth). SGS-90 differs from the WGD84, which is used by GPS system, by less than 0.4 m in any direction [3].

GLONASS has its own time scale called GLONASS time, which is synchronized within 1 second of UTC time. The navigation message has the data necessary to convert between GLONASS time and UTC time.

GLONASS Satellite transmissions use the frequency division multiple access (FDMA) technique, to differentiate between the signals of different satellites, in which each satellite uses a separate channel, and provides precision (SP) and high precision (HP) signal at different clock rates. The Hp signal has a larger bandwidth than the SP signal. The SP signal is available for civilian use with an accuracy of 50 to 70 m; a higher accuracy can be achieved using dual-frequency of the HP signal.

GLONASS system uses a satellite constellation to provide the GLONASS receiver with six to twelve satellites at most of times. Same as GPS system a minimum of four satellites in view allows GLONASS receiver to determine the longitude, latitude, height and time of its current position.

A. GLONASS Segments

Space segment of GLONASS consists of 24 satellites in three orbital planes. Among these satellites there are 21 active satellites, while the other three satellites are used as spares. This constellation assures that at least five satellites are available in the view at any point in the earth. A constellation of 21 satellites provides a continuous and simultaneous visibility of at least four satellites over 97% of the earth surface, while a constellation of 24 satellites provides a continuous and simultaneous visibility of at least five satellites over more than 99% of the earth surface [1].

Control Segment consists of the system control center located in Kranznamensk Space Center about 70 km southwest Moscow. The center is connected with 8 tracking stations distributed across Russia. These stations are responsible for tracking and monitoring the satellites status in the orbits, determining the ephemerides and satellite clock offsets with respect to GLONASS time, and transmitting this information to the system control center via radio link once per hour.

B. GLONASS Signals

GLONASS provides high accuracy signal for military use and standard accuracy signal for civil use. The used carrier frequencies are $L1(1602 - 1615.5\ MHz)$ and $L2(1246 - 1256.5\ MHz)$. The signals are modulated by two binary codes, the standard accuracy signal (C/A code) and the high accuracy signal (P code); the C/A code is only modulated onto L1, while P code is modulated onto L1 and L2. The P code signal is not encrypted. The Russian Ministry of Defense does not recommend the unauthorized use for P code, because P code may be changed without prior notice to unauthorized users [1].

New generation GLONASS-K satellite was successfully launched in February 2011. Besides L1 and L2 carriers, these satellites transmit signals in L3 carrier frequency ($1204.704\ MHz$). This third frequency increases the reliability and accuracy where developers announced that it will be used especially for safety of life applications.

C. GLONASS Navigation Message

The navigation message includes information about the satellites orbits, satellite health status, correction data, and the almanac data about all satellites within GLONASS constellation. In addition, it includes the correction to GLONASS time relative to UTC (SU) and the time difference between GLONASS system time and GPS system time.

The data pattern is of the navigation message is generated as continuously repeated superframes. A superframe has duration of 2.5 minutes and consists of five frames, each of 30 seconds duration. The frame consists of 15 strings of 100 bit length. Each string has 2 seconds duration and holds 85 data bits and a time mark. The whole superframe consists of 5 frames.

The first five strings contain the data relate to the satellite that transmits given navigation signal. The strings include ephemerides data, time tag corresponding to the beginning of the frame, the satellite health, the satellite clock correction, and the variation of the satellite carrier frequency. The ephemerides data are valid for several hours. The data about all available satellites in orbit are included in the Strings 6 to 15, where the almanac data occupy two strings. The last two string of the fifth frame are left empty for modernized use. The navigation message of high accuracy signal is longer. It needs 12 minutes and contains more precise information. On the other hand, the superframe is divided into 72 frames; each frame includes five strings, each string is 100 bit length.

V. GALILEO

Looking for participating the existed GNSS systems, Europe tried to take part in GPS's control and development. However, this was not acceptable by US. Therefore, Europe tried starting cooperation with Russia to develop GLONASS system, but there was no interest from the Russian side. Finally, European countries took the decision to develop their own GNSS system. In 2002 the European Union (EU) and European Space Agency (ESA) agreed to introduce their own GNSS called Galileo as an autonomous, alternative, and competitive GNSS to GPS and GLONASS. The Galileo system is scheduled to be working in 2012. The European commission in 2000 estimated the cost of Galileo system to reach 3.4 billion Euros including an operation phase until 2020. Nevertheless, they estimated that the cost of two days of GPS service interruption in 2015 would cost Europe's transport and financial sectors about one billion Euros [1]. In 2002 a complete definition of Galileo project for the main characteristics and performance summarized in high level document. First experimental Galileo satellites, GIOVE-A and GIOVE-B, were launched in 2005 and 2008. While the first two Galileo satellites were launched on October 2011 [10].

The Galileo constellation will include 30 satellites. The satellites transmit on several frequencies and will provide different services for civilian, commercial, safety of life, and emergency assistance. They also considered the combined service level of Galileo and other GNSS systems (GPSS and GLONASS).

Galileo has its own system time, called Galileo System Time (GST). GST is a continuous atomic time scale with a nominal constant offset with respect to the International Atomic Time (TAI). GST starts at midnight between Saturday and Sunday [1]. GST consists of week number(WN), and time of week (TOW). The WN covers 4096 weeks before it reset to zero. A week has 604,800 s and it is rolled over to 0 at the midnight between Saturday and Sunday. The navigation message includes the parameters that are needed for the conversion of GST to UTC and also GPS Time. The relation between GST and UTC is defined base on the difference between UTC and TAI which is an integer number of seconds. For example, on January 1, 2003 the difference was $TAI - UTC2003 = +32s$ [11].

A. Galileo Segments

Space segment of Galileo will include a constellation of a total of 30 satellites, 27 are operational and 3 spare satellites. These satellites are spaced around the plane in three circular medium earth orbits (MEO) with 23.600 km Altitude. Galileo constellation guarantees that at any point on the earth, there will be at least 6 satellites in the view.

Ground segment consists of two ground control center responsible for Central Processing Facility; they are located in Oberpfaffenhofen-Germany and Fucino-Italy. Moreover, the control centers are connected with five tracking and control stations, 9 C-band uplink stations, and about 40 Galileo sensor stations

User segment of Galileo must be developed in parallel with the core system to ensure that the receivers and users will be available in time when the Galileo reach its full operational capabilities. Galileo provides test user segment specifications and implementations to develop receivers to experiment and validate the Galileo service and provide a proof of the system performance. There are several running projects and there are several receivers' product lines that introduce Galileo receivers (e.g., GARDA receiver).

B. Galileo Signals

Galileo will provide ten navigation signals in the frequency ranges $1164 - 1215$ MHz (E5a and E5b), $1215 - 1300$ MHz (E6) and $1559 - 1592$ MHz (E2-L1-E1). $E2 - L1 - E1$ includes the GPS frequency band L1. Also in the middle, the frequency range $1544.05 - 1545.15$ MHz defined as Search and Rescue (SAR) uplink and $406.0 - 406.1$ MHz SAR downlink frequencies. All the Galileo satellites will share the same nominal frequency, making use of Code Division Multiple Access (CDMA) compatible with the GPS approach [12].

Four different types of data are carried by the different services. First, open service (OS) data, which are transmitted on the E5a, E5 band E2-L1-E1 carrier frequencies. OS data accessible to all users and include mainly navigation data and Search and Rescue Service (SAR) data. SAR service comes as a contribution to the international Cospas Sarsat system. In which Galileo satellites detect emergency messages at the SAR uplink frequency from distress emitting beacons, and forward the emergency messages to the SAR ground segment in the SAR downlink frequency band. Afterwards the SAR ground segment is responsible to recover a valid beacon message, determine the location of the beacon and transmit the distress information to the associated Mission Control Centre (MCC) [13] [14]. Second, Safety of Life (SoL) data, which include mainly integrity and Signal in Space Accuracy (SISA) data, are transmitted on the E5a, E5b and E2-L1-E1 carrier frequencies. Third, Commercial service (CS) data transmitted on the E2-L1-E1, E5b, E6 carriers. All Commercial Service (CS) data are encrypted and are provided by some service providers that interface with the Galileo Control Centre. The service providers offer a direct access to those commercial data. However, the access to the integrity data may be controlled. The fourth one is Public Regulated Service (PRS) data, transmitted on E6 and L1 carrier frequencies with encrypted ranging codes [12].

C. Galileo Navigation Message

There are different types of data content have been introduced for Galileo navigation message: the navigation data, integrity data, the supplementary data, the public regulated data, and data for SAR operation. These different data content types define four navigation messages types [1]: 1-Freely accessible navigation message, 2-Integrity navigation message, 3-Commercial navigation message, and 4-Govermental navigation message. These types express the content of the related service. The Navigation message is structured as frames, each frame contains several subframes, and each subframe contains several pages. The page contains a synchronization word (SW), a data field, a cyclic redundancy check (CRC) bits for error detection, and tail bits for the forward error correction (FEC) encoder containing all zeros.

VI. Other GNSSs

A. Compass

Compass [15] is the Chinese navigation system, which is still in the construction phase. The Chinese government decided to build their own global navigation system in 1980. They developed a navigation system called Beidou, it consists of 3 satellites. Since 2000, it provides its service only to the China and the neighboring regions covering an area of about 120 degrees longitude in the Northern Hemisphere. Compass comes in place as a second generation of Beidou Satellite Navigation System, which is planned to provide navigating service for Asia-Pacific region by 2012, and provide global Navigation service by 2020. Compass will provide a civilian service with accuracy of 10 meters, and 50 nanoseconds in time accuracy, and a military and authorized user's service, providing higher accuracies. Compass constellation will consist of 35 satellites including 5 geostationary orbit (GEO) satellites, 3 in highly inclined geosynchronous orbits (IGSO) and 27 medium Earth orbit (MEO) satellites that will offer complete coverage of the globe [16]. The fifth geostationary orbit satellite was launched in December 2011. Compass official governmental website announced that this fifth satellite completes the construction of the basic regional navigation system for servicing China and will be operational by the end of the year.

Frequencies for Compass are allocated in three bands, which are 1575.42 MHz (B1), 1191.795 MHz (B2) and 1268.52 MHz (B3) [17]. Both Open Service (OS) and Authorization Service (AS) are provided in the B1 band, while only OS in the B2 band and AS in the B3 band, which overlap with Galileo. The fact of overlapping could be convenient from the point of view of the receiver design, but on the other hand raises the issues of inter-system interference, especially within E1 and E5 bands, which are allocated for Galileo's publicly regulated service [18].

B. QZSS

The Quasi Zenith Satellite system (QZSS) is a regional navigation satellite system that is in the development phase by the Advanced Space Business Corporation (ASBC) team, which is authorized by the Japanese government in 2002. QZSS covers regions in East Asia and Oceania centering on Japan, and is designed to ensure that users are able to receive positioning signals from a high elevation at all times. The plan is to place the satellites in High Elliptical Orbit (HEO), which helps to overcome the objects (building) interception for the satellites signals. The system also improves positioning accuracy by transmitting signals L1C/A, L1C, L2C and L5 that are equivalent to modernized GPS signals [19]. QZSS uses the time base of GPS. They use the Japanese satellite navigation Geodetic System (JGS) to represent the calculated Cartesian coordinates. The difference between JGS and WGS84 used by GPS is 0.2m. The navigation message is also same as the navigation message broadcasted by GPS system.

There are several regional satellite systems that are in different design and development phases, there is the Indian Regional Navigation Satellite System (IRNSS) that will provide the service to India region. There are also GNSS augmentation systems, which are external to the GNSS systems but it is used to maintain high positioning accuracy by providing additional information such as corrections and integrity information. One of the systems that are deployed in North America called the Wide Area Augmentation System (WAAS), WASS is developed by The Federal Aviation Administration (FAA) for using in precision flight and transportation systems, where the accuracy of GPS system is not sufficient for such precision systems. WAAS consists of geostationary satellites and ground stations that provide GPS signal corrections. It provides an ephemeris correction and localized ionospheric delay information. The geostationary satellites are set at a high altitude, which helps to increase the accuracy of calculated position; these satellites transmit the same ranging signal of the GPS satellites, which give the possibility to use them as additional range measurement with GPS. The WAAS broadcast message

TABLE II
GPS, GLONASS, GALILEO, AND COMPASS COMPARISON

Characteristics	GPS	GLONASS	Galileo	Compass
First launch	February, 1978	October, 1982	December, 2005	April, 2007
Full operational capability	February, 1995	January, 1996 - December, 2011	2012,2013	up to 2020
Funding	public	public	public & private	public
Nominal number of SV	24	24	27	27
Orbital planes	6	3	3	3
Orbit inclination	55°	64.8°	56°	55°
Semi-major axis	26,560 km	25,508 km	29,601 km	21,500 km
Orbit plane separation	60°	120°	120°	–
Revolution period	11h 57.96 min	11h 15.73 min	14h 4.75 min	12h 35 min
Geodetic reference system	WGS-84	PE-90	GTRF	CGS2000
Time system	GPS time, UTC (USNO)	GLONASS time, UTC(SU)	Galileo system time	Bei Dou System Time (BDT)
Signal separation	CDMA	FDMA	CDMA	CDMA
Number of frequencies	3-L1,L2,L5	one per two antipodal SV	3(4)-E1,E6,E5(E5a,E5b)	3-B1,B2,B3
Frequency [MHz]	L1: 1,575.420	G1: 1,602.000	E1: 1,575.420	B1: 1,575.420
	L2: 1,227.600	G2: 1,246.000	E6: 1,278.750	B2: 1,191.795
	L3: 1,176.450	G3: 1,204.704	E5: 1,191.795	B3: 1,268.520
Number of ranging codes	11	6	10	–

improves GPS signal accuracy from 100 meters to approximately 7 meters. Another system, which is similar to WAAS, is the European Geostationary Navigation Overlay Service (EGNOS), EGNOS provides GPS and GLONASS corrections, and it gives a position accuracy of better than three meters. The WAAS and EGNOS are compatible, while same receiver can use both systems. Moreover, the Japanese augmentation system MSAS and the Indian augmentation system GAGAN are also compatible with WAAS and EGNOS messages.

VII. COMPARISON BETWEEN GPS, GLONASS, GALILEO AND COMPASS

Currently, there are four GNSS systems in different development phases or already reaching a fully operational GNSS. The United States NAVSTAR Global Positioning System (GPS) is the only system with fully operational capabilities. It has been widely used in the recent years. The Russian GLONASS is restored a full operation capabilities recently in December, 2011. The European Union's Galileo positioning system is a GNSS in the deployment phase. It is planned to reach full operational capabilities in 2012. China has rapidly started the development of their global navigation system COMPASS, which is currently used as a regional navigation system in China; the plane is to reach global full operation capabilities in 2020. There are also parallel development of different satellites navigation systems for different countries such as India and Japan. The main difference between these four navigation systems is the space segment. GPS consists of 24 active satellites in 6 orbital planes. GLONASS consists of 24 satellites in three orbital planes. Galileo consists of 30 satellites, 27 of them are operational, while 3 are spare satellites spaced around the plane in three circular MEO in three orbital planes. Compass consists of 35 satellites including 5 GEO satellites and 30 MEO satellites. This means that Galileo and Compass MEO satellites are above the GPS and GLONASS satellites. GLONASS differs from the other GNSSs in that each satellite has its own frequencies but the same code whereas GPS, Galileo, and Compass use the same frequencies but have different codes. GLONASS uses FDMA. On the other hand, GPS, Galileo and Compass use CDMA. Table II shows a comparison between GPS, GLONASS, Galileo, and Compass systems.

VIII. CONCLUSION

Different GNSS systems are designed to be compatible, which enable using more than one GNSS system to calculate the position. For example using two GNSS systems increases the position accuracy, while increasing the number of satellites in the receiver view will increase to the double and also DOP value will decrease. Moreover, the combined signals will improve the code measurements, reduce the code noise level, and improve ionospheric and tropospheric propagation models. Now a day's the direction goes towards combining signals from multiple GNSSs to maintain greater availability, higher performance, higher reliability, and higher accuracy than using only one GNSS system.

On the other hand the frequency bands sharing between different GNSSs causes interference between available signals from different GNSSs (e.g. the interference between the Compass and Galileo signals in B1/E1 and B2/E5 bands), which leads to performance degradation. A lot of research focusing on measuring the interference between the different GNSSs' signals frequencies, which happened due to the limited frequency resources and the growing number of navigation satellite signals.

REFERENCES

[1] B. Hofmann-Wellenhof, H. Lichtenegger, and E. Wasle, *GNSS - Global Navigation Satellite Systems: GPS, GLONASS, Galileo, and more*. Springer; 1 edition, December 2007.

[2] "Official U.S. Government information about the Global Positioning System (GPS) and related topics," November 2011. [Online]. Available: http://www.gps.gov/

[3] N. Harper, *Server-Side GPS and Assisted-GPS in Java*, ser. Artech House GNSS Technologies and Applications. Artech House, 2009.

[4] A. Küpper, *Location-Based Services: Fundamentals and Operation*. Wiley; 1 edition, October 2005.

[5] P. Daly and I. Kitching, “Characterization of NAVSTAR GPS and GLONASS on-board clocks,” in *IEEE Aerospace and Electronics Systems Magazine*, July 1990, pp. 3–9.
[6] “WGS 84 IMPLEMENTATION MANUAL,” February 1998. [Online]. Available: http://www2.icao.int/en/pbn/ICAO Documentation/GNSS and WGS 84/Eurocontrol WGS 84.pdf
[7] T. Suzuki, M. Kitamura, Y. Amano, and T. Hashizume, “High-Accuracy GPS and GLONASS Positioning by Multipath Mitigation using Omnidirectional Infrared Camera,” in *2011 IEEE International Conference on Robotics and Automation*, May 2011, pp. 311–316.
[8] C. Rizos, *Principles and Practice of GPS Surveying*, 1999. [Online]. Available: http://www.gmat.unsw.edu.au/snap/gps/gps_survey/principles_gps.htm
[9] “Federal Space Agency: Information Analytical Center,” December 2011. [Online]. Available: http://www.glonass-center.ru
[10] “European Space Agency,” December 2011. [Online]. Available: http://www.esa.int
[11] C. R. Rao, *Global Navigation Satellite Systems*. Tata McGraw-Hill Education, June 2010.
[12] G. W. Hein, J. Godet, J. luc Issler, J. christophe Martin, R. Lucas-rodriguez, and T. Pratt, “Status of galileo frequency and signal design,” in *in CDROM Proc. ION GPS*, 2002, pp. 34–37.
[13] L. Gang, H. Bing, F. Hui, and Z. Wenda, “A novel TOA estimation algorithm for SAR/Galileo system,” in *2008 IEEE International Conference on Systems, Man and Cybernetics (SMC 2008)*, October 2008, pp. 3554–3557.
[14] R. Yi-hang, L. Yu-qi, H. Xiu-lin, and K. Ting, “Evaluation of Intersystem Interference between Compass and Galileo,” *Journal of Convergence Information Technology, Volume 6, Number 6*, pp. 288–299, June 2011.
[15] C. Cao, G. Jing, and M. Luo, “COMPASS Satellite Navigation System Development,” November 2008. [Online]. Available: http://scpnt.stanford.edu/pnt/PNT08/Presentations/
[16] G. Xingxin Gao, A. Chen, S. Lo, D. De Lorenzo, T. Walter, and P. Enge, “Compass-m1 broadcast codes in e2, e5b, and e6 frequency bands,” *IEEE Journal of Selected Topics in Signal Processing*, vol. 3, pp. 599–612, August 2009.
[17] C. Wu and C. He, “Interference Analysis among Modernized GNSS,” in *International Conference on Computational Problem-Solving (ICCP), 2011*, October 2011, pp. 669–673.
[18] J. Ye, Y. Jiang, J. Zhao, and J. Guo, “Study of sar imaging with compass signal,” *SCIENCE CHINA Physics, Mechanics and Astronomy*, vol. 54, pp. 1051–1058, 2011.
[19] “Quasi-Zenith Satellites System (QZSS),” December 2011. [Online]. Available: http://qzss.jaxa.jp