Global Navigation Satellite Systems and their wide Range of Applications

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The Global Positioning System (GPS) was once the only operational global navigation satellite system (GNSS), and it was used all over the world to access location-based services (LBS). With the Russian GLONASS navigation system, which became fully operational at the end of 2011 and with the future deployment of China's Compass and Europe's Galileo navigation there will be increased focus on the capabilities and applications of such systems. This article gives an overview of the different navigation systems, explains the navigation channel and generic approach used by a commercial standard receiver to calculate a user position and generally describes channel acquisition and tracking. GNSS applications such as differential GNSS (D GNSS) and multiple frequency-band navigation, their complexity and benefits are also presented.

Global navigation satellite systems are made up of satellites spanning the globe in a set of defined orbits and aim to provide accurate, uninterrupted and global three-dimensional (3D) position and velocity information to users equipped with appropriate receiving equipment. GPS has been operational for some time and GLONASS has just become operational, whereas Galileo and Compass navigation systems will be deployed gradually in the next ten years and may be used in addition to GPS to improve location-based services.

A GNSS network is composed of satellite space vehicles (SV), user equipment (UE) and control stations (CS). Satellite transmissions are referenced to highly accurate atomic clocks onboard the satellites that are synchronous to the GNSS system time base.

The worldwide control network monitors the health and status of the satellites and uploads the satellite navigation data, which is composed of immediate 'ephemeris' navigation data and non-immediate 'almanac' navigation data from different CS. This data, along with the ranging information tracked at the UE from at least four satellites, enables the receiver module to calculate the satellites' positions and subsequently the 3D position of the UE.

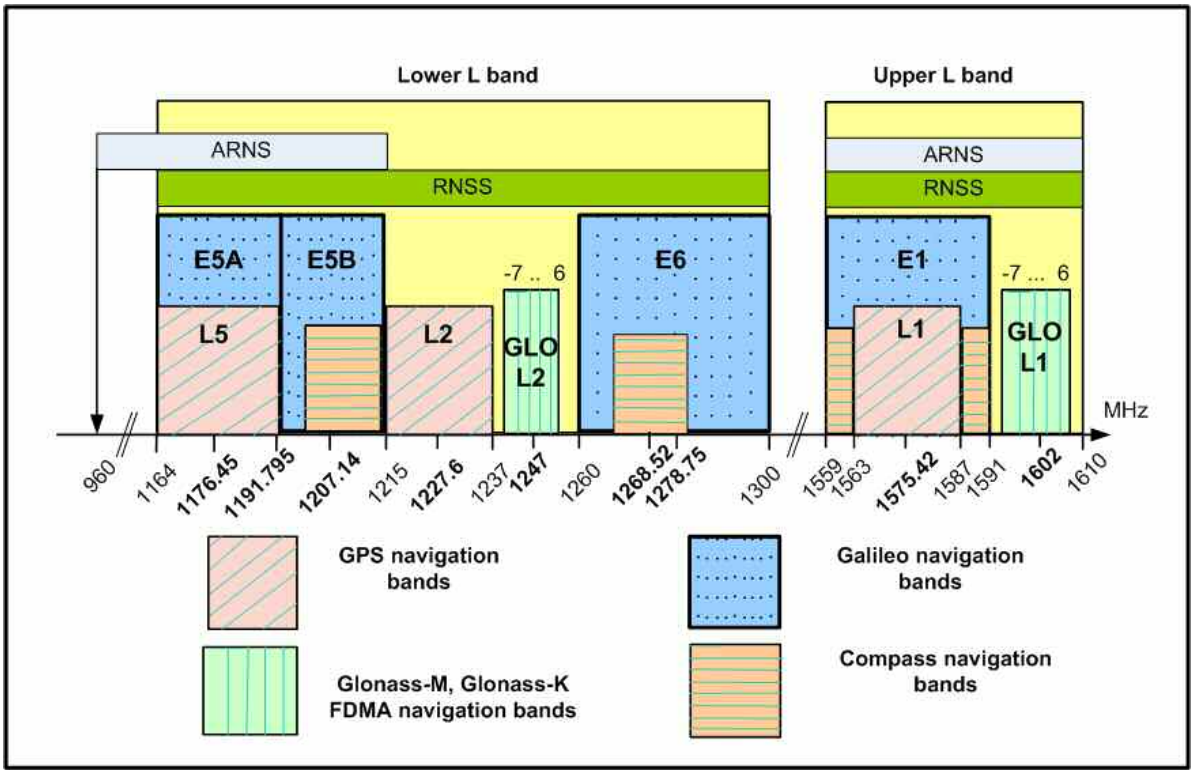

Fig 1. GNSS navigation RF bands

GPS

The nominal GPS satellite constellation consists of 24 middle earth orbit (MEO) satellites arranged in six orbital planes with four satellites per plane. The satellites broadcast ranging codes and navigation data on three frequencies – L1 (1,575.42 MHz), L2 (1,227.6 MHz) and L5 (1,176.45 MHz) – using code division multiple access (CDMA), as can be seen in **Figure 1**. Each satellite transmits on these bands, but with different ranging codes than those employed by other satellites. These codes were selected because they have low cross-correlation properties, thereby minimizing the interchannel interference.

GLONASS

GLONASS is an FDMA-based GNSS. A subcarrier is allocated but not reserved to a specific satellite. GLONASS became fully operational at the end of 2011, when the three nominal orbital planes were completely filled by eight satellites each. All satellites additionally share one spreading code that is optimized for noise suppression. Two satellites can share the same frequency number if they are located at diametrically opposite antipodal points on the same orbit, and therefore cannot be seen by a user on the Earth at the same time. Subcarriers are allocated to GLONASS in the upper and lower bands as follows:

$$(1)\quad \begin{aligned} F_{L1}(MHz) &= 1602 + 0.5625 \cdot k \\ F_{L2}(MHz) &= 1246 + 0.4375 \cdot k \end{aligned}$$

where the frequency number k is between –7 and 6 for all GLONASS-M satellites launched after 2005, and between 0 and 12 for all GLONASS satellites launched before 2005.

The modernization of GLONASS as part of the GLONASS-K program will be continued. In the future, Russian satellites are to broadcast optimized CDMA signals in the GPS and Galileo L1/E1 bands as well as in other bands, in order to harmonize the GLONASS system with GPS and Galileo.

GALILEO

Galileo is an independent European GNSS. It is expected to be partially operational with 18 satellites in 2015 and fully operational with 30 satellites in 2020. One of the benefits of Galileo is that it can complement GPS to provide better navigation performance mainly in urban areas. The system uses CDMA to modulate the satellite signals and thus employs a dedicated spreading code for each space vehicle.

In addition, GPS and Galileo are supposed to share the same frequencies in the upper RNSS band (also called L1/E1) and minimize inter-/intrasystem interference by selecting orthogonal pseudo random noise (PRN) and applying binary offset carrier (BOC) modulation, as shown in **Figure 2**.

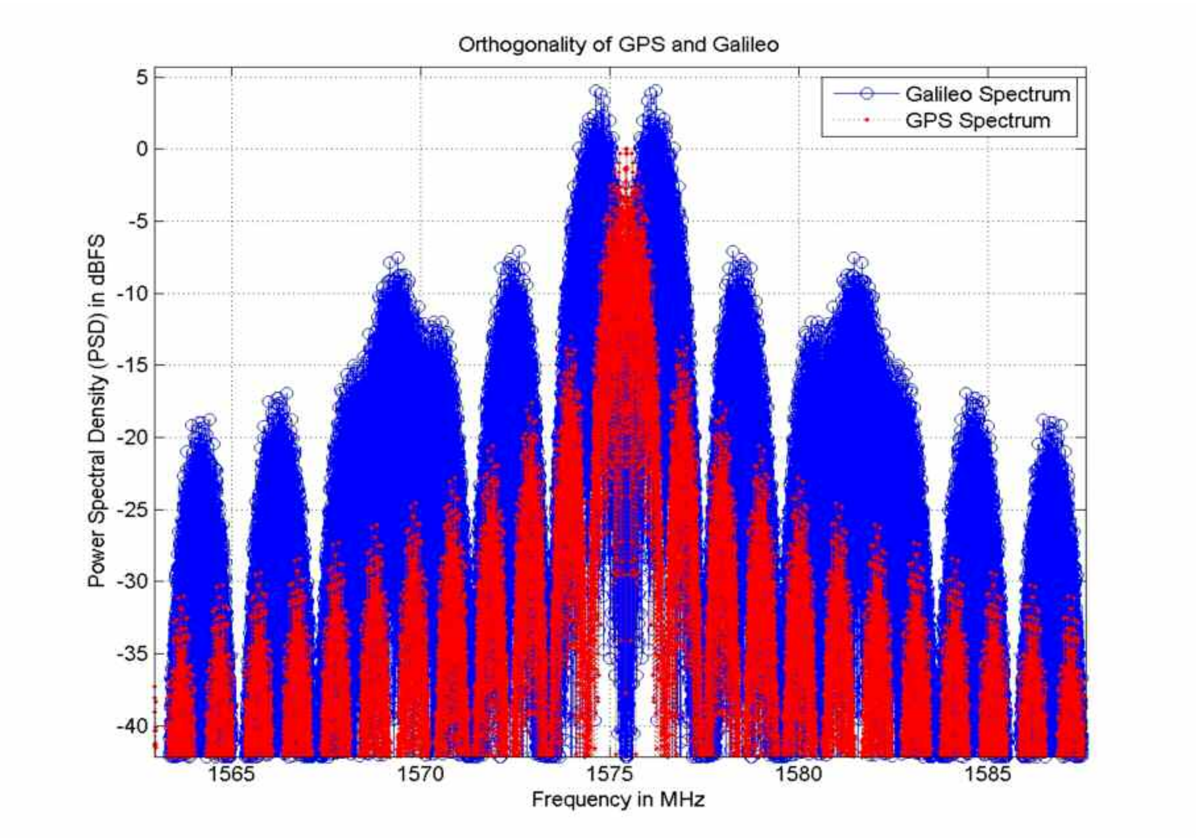

Fig 2. Power spectral density of GPS L1 C/A and Galileo E1

COMPASS

Compass is a global navigation system that will not be fully operational before 2020. Because the Galileo project has been delayed, China's regional Compass satellite system Beidou-2, designed to cover large parts of Asia, is scheduled to become operational in 2012 and broadcast on the same bands pre-allocated to Galileo (see Figure 1). These bands can then be acquired solely by the Chinese Compass/Beidou-2 navigation program.

LOCALIZATION SYSTEM MODEL

Navigation employs ranging to determine a user's position. Therefore, taking ranging measurements from different satellites (which may belong to different navigation satellite systems) makes 3D positioning possible. The geometric range R_i is defined as the line of sight (LOS) distance from the satellite to the user as follows:

(2) $R_i = \sqrt{(x_i - x_u)^2 + (y_i - y_u)^2 + (z_i - z_u)^2}$

where (x_i, y_i, z_i) *for all i* and (x_u, y_u, z_u) represent the coordinates of all SV_i and UE, respectively, on an orthonormal basis.

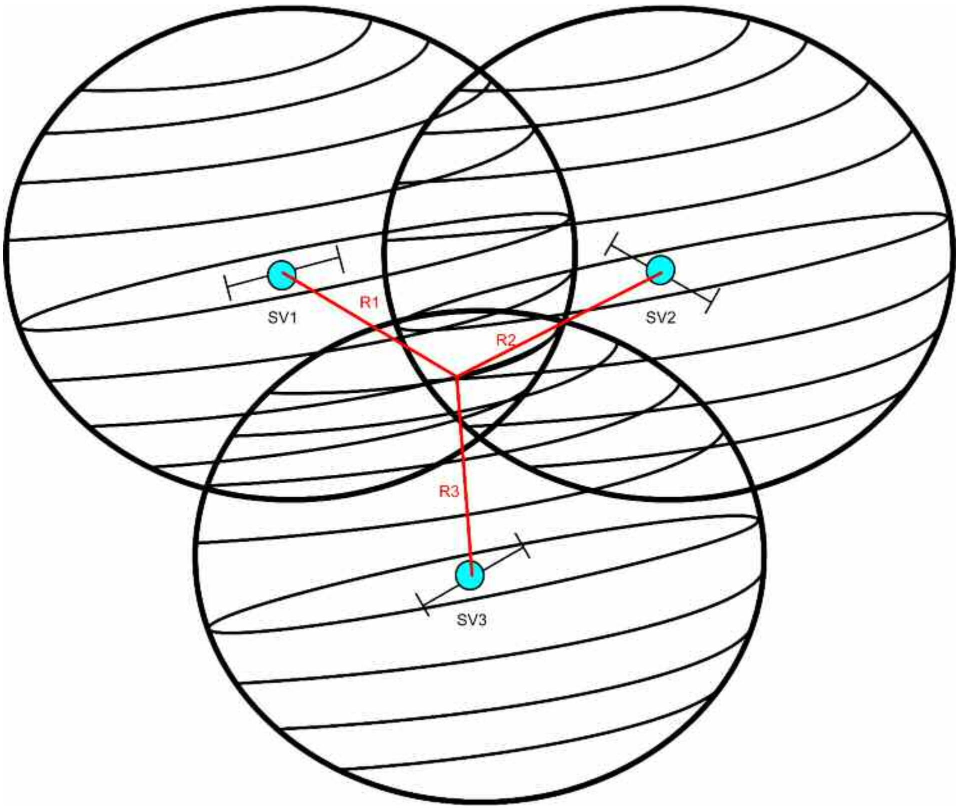

Fig 3. Illustration of localization using ranging signals from three satellites

Knowing the position of three satellites and the absolute geometric range at a given UE location from each satellite allows users to locate their position at the intersection of three spheres centered around the satellites, each having a radius R_i. This basic trilateration approach is illustrated in **Figure 3**.

The geometric range R_i (equivalent to LOS propagation) is not actually available at the UE, since the satellite signal propagation time gets distorted due to different factors such as refraction in the ionosphere and the troposphere, multipath propagation and satellite clock ambiguities. The distorted version of the geometric range is the pseudorange p_i, which is the distance crossed by the ranging signal of a specific satellite to reach a user on the Earth. If t_i is defined to be the propagation time of the GNSS signal from sv_i to the UE then $p_i = t_i . c$, where c is the speed of light. The ranging observation t_i and consequently p_i can be directly calculated from the tracked code and carrier phase of the corresponding tracking channel at the UE.

The navigation solution based on the aforementioned trilateration concept requires resolving the ambiguity in the pseudorange of every tracked satellite and thereby calculating R_i using the indirectly measured p_i and the GNSS satellite-UE channel model that relates R_i to p_i.

GNSS SATELLITE-UE CHANNEL MODEL

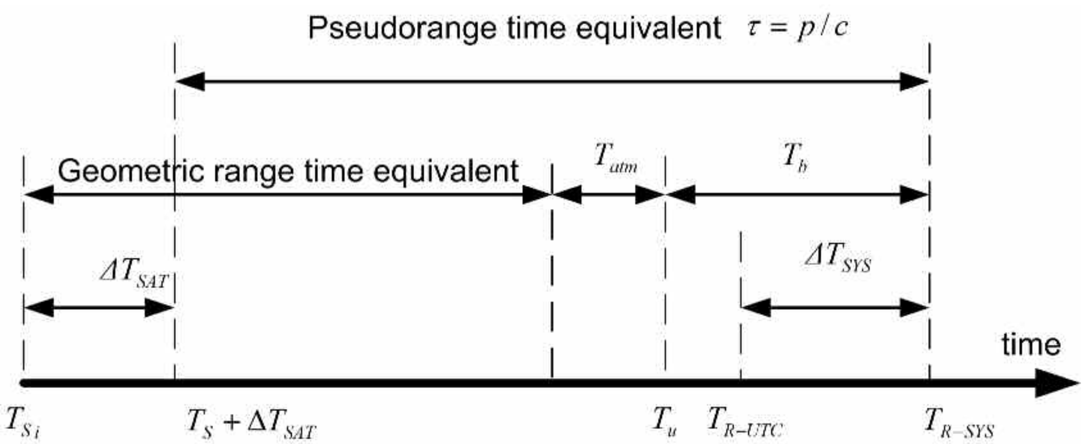

Fig 4. Illustration of satellite-UE channel model

As shown in **Figure 4**, the generic channel model that can be used to relate the geometric range to the pseudorange of SV_i (space vehicle) can be expressed as:

(3) $p_i = \tau_i \cdot c = R_i + (T_{atm_i} + T_b - \Delta T_{SAT_i}) \cdot c$

where T_b corresponds to the receiver time bias, T_{atm} to the atmospheric ambiguities and ΔT_{SATi} to the satellite clock errors. The geometric range R_i of a satellite (the radius of the trilateration sphere) can be calculated from the observed t_i using equation (3). The UE location is determined by calculating the geometric range of at least four satellites and the corresponding satellite coordinates (x_i, y_i, z_i), which are the centers of the trilateration spheres at T_{si} , where

(4) $T_{S\,i} = T_{R-UTC} + \Delta T_{SYS} - \tau_i - \Delta T_{SAT_i}$

T_{SYS} is the time difference between a specific GNSS system time base and a common system time base as UTC can be calculated. TR_{-UTC} corresponds to the receiver time in UTC (Universal Time Coordinate).

Least square algorithms are usually used for UE location and time calculation. Other weighted least square algorithms with weights assigned proportionally to the measured carrier-to-noise ratio (C/N) of every tracked satellite are also very widely used in commercial receivers.

T_b, T_{atmi} and ΔT_{SATi} are the distortion parameters that differentiate the geometric range from the pseudorange and will be described in the following subsections.

- Receiver time bias

The ranging observations (τ_i) are actually differential; the UE does not have an atomic clock synchronized to a reference time base, the thing all satellites in a specific GNSS share. This is the reason why the same bias T_b is implicitly applied at the UE for all satellites in the generic channel. The introduction of this bias imposes the requirement of having at least four satellite ranging observations in order to calculate location and time.

- Atmospheric corrections

The ionosphere is a dispersive medium located at altitudes between 80 km and 1000 km above the Earth's surface. The ranging signal gets refracted while crossing the ionosphere, thereby causing a deflection from the LOS.

As explained in [1], the ionosphere refraction indexes that lead to the determination of the phase and group delay of a GNSS signal in the ionosphere are n_p and n_g, respectively, where

(5) $n_p = 1 - c_2 / f_c^2 \quad and \quad n_g = 1 + c_2 / f_c^2$

c_2 is a constant related to the density of the electrons released by the ionization of gas molecules by the ultraviolet (UV) rays from the sun, and f_c is the carrier frequency of the signal crossing the ionosphere.

It can be deduced from equation (5) that the ionosphere's caused delay on the code phase T_{ion_i} is equal to the caused advance on the carrier phase and that T_{ion_i} is inversely proportional to f_c^2 ; this is why multiple frequency GNSS receivers (e.g. GPS L1/L2 receivers) are used to compensate for the ambiguities in the ionosphere.

Single frequency GNSS receivers use different models to estimate the ambiguities in the ionosphere. Klobuchar, the model employed by standard GPS satellites, assumes different thicknesses of the ionosphere's layer when observed during the day or at night. The tuning parameters for Klobuchar are transmitted in the almanac part of the GPS navigation message. The error in the estimation of T_{ion_i} is one of the most significant factors affecting the accuracy of position fixing in a standard single frequency GNSS receiver.

A different model is usually used by UE to estimate the troposphere's ambiguities T_{Tropo_i} . STANAG is the most popular model utilized in commercial receivers to compensate for these ambiguities.

The atmospheric delay referenced to a LOS propagation includes the delays of the ionosphere and troposphere:

(6) $T_{atm_i} = T_{ion_i} + T_{Tropo_i}$

- Satellite clock corrections

The satellite time scale can not be perfectly synchronized to the system time of the respective GNSS. Control stations measure and model the phase and frequency drift in the satellite clock and upload the information to the satellite, which updates the satellite clock correction parameters as part of the ephemeris of the navigation message. The update rate is usually 2 h for GPS and 30 minutes for GLONASS.

Other gravitational and relativistic effects on the satellite clock can be calculated by decoding the ephemeris of the different satellites at the UE. The sum of all these ambiguities is ΔT_{SAT_i}.

- System time transformation
The satellite coordinates corresponding to the centers of the trilateration spheres should be calculated at T_{S_i} which depends on the known UTC time, ΔT_{SAT_i}, ΔT_{SYS} and τ_i measurements, as shown in equation (4). This subsection describes how ΔT_{SYS} (the time difference between a specific GNSS system time base and a common system time base such as UTC) can be calculated.

A reference time base has to be used for all GNSS in a hybrid receiver, since a reference time scale is needed for the τ_i observations. A suitable time base for this purpose is the universal time coordinate (UTC) system time. For the sake of simplicity, it is assumed unique in the following. If T_{R-UTC} corresponds to the receiver time in UTC, then

(7) $$\Delta T_{SYS} = T_{R-SYS} - T_{R-UTC} = a_0 + a_1 \cdot \Delta t + b \cdot T_{leap}$$

corresponds to the time offset between UTC and the specific GNSS.
a_0 and a_1 correspond to the phase shift and frequency drift between UTC and GNSS system time, respectively. They are usually transmitted in the almanac part of the navigation message of all satellites of a GNSS. T_{leap} is an integer time offset associated with an uninterrupted GNSS time base, e.g. GPS and Galileo “b=1”. GLONASS system time is corrected similarly to UTC “b = 0”. Currently $T_{leap} = 15\ s$.
The phase shift of GLONASS relative to GPS system time was formerly not transmitted in the almanac of GLONASS, which is why getting a fix using a hybrid GPS/GLONASS receiver previously required an additional GLONASS satellite, i.e. altogether five satellites. A location fix can be obtained with all GLONASS-M using only four satellites, due to transmission of the relative phase shift information.

SATELLITE POSITION CALCULATION

To determine the location of the UE, first the position of all satellites must be determined. According to Newton’s laws, the gravitational force exerted by the Earth’s mass *M* on a satellite of mass *m* located at a distance *r* is:

(8) $$\mathbf{F} = m \cdot \mathbf{a} = -G \frac{m \cdot M}{r^3} \mathbf{r}$$

G is the universal gravitational constant; *r* is the distance between the center of gravity of the Earth and the satellite in an Earth-centered inertial (ECI) orthonormal xyz coordinate system whose x and y axes do not rotate with the Earth. In equation (8) $r = \| \mathbf{r} \|$. The transformation from the differential equation’s ECI coordinate system to the UE coordinate system, which rotates with the Earth and is also called an Earth-centered, Earth-fixed (ECEF) system, is merely a rotation.

Equation (8) should be rotated from ECI to ECEF to obtain a differential equation that can be used to calculate the satellite coordinates in the same UE's ECEF coordinate system. Only then can the trilateration generic concept work properly.

- ECI vs. ECEF

The ECI coordinate system is centered at the Earth's center of gravity. The xy plane is taken to coincide with the Earth's equatorial plane. As described in [2] (section 6), GPS ECI uses the orientation of the equatorial plane at 12:00 UTC on January 1, 2000. The x-axis is fixed in the direction of the vernal equinox (see **Figure 6**). The z-axis is normal to the xy plane.

ECEF, on the other hand, is the coordinate system used to calculate the position of UE, since it rotates with the Earth. The x-axis points in the direction of 0° longitude. Therefore, the transformation between ECI and ECEF is a rotation of the xy plane. The angle of rotation is derived from the Earth's sidereal time at any given moment.

- Motion Equation

The acceleration vector **a** in equation (8) is the second derivative of **r**. Consequently, the two-body mass differential equation of motion in ECI is:

$$(9)\quad \frac{d^2\mathbf{r}}{dt^2} = -\frac{G \cdot M}{r^3}\mathbf{r}$$

where d^2/dt^2 is the second derivative operator. The solution to equation (9) can be shown as an ellipse with its focal point located at the center of gravity of the Earth (see **Figure 5**). The true anomaly v represents the angle of the satellite in its orbit referenced to the perigee, the orbital point at the shortest distance to the Earth. The semi-major axis of the orbit a and the eccentricity e define the shape of the elliptical orbit and are determined by the location of and the direction in which the satellite is released from its space shuttle.

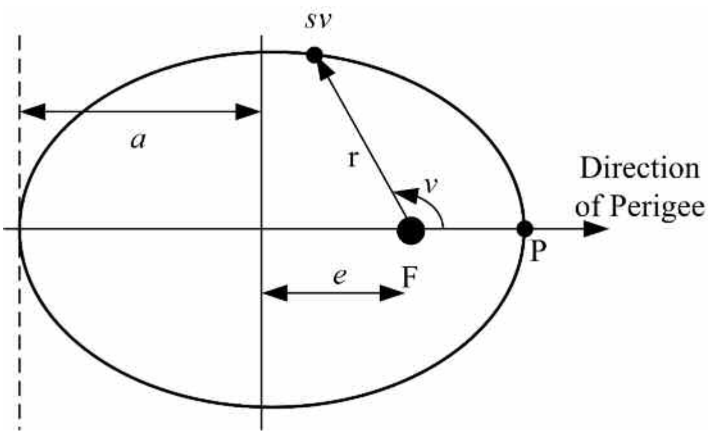

Fig 5. GNSS orbital parameters

However, equation (8) does not describe the motion of the satellite precisely, since ambiguities are caused by the solar and lunar gravitational forces and by the fact that the Earth is not perfectly spherical. This is the reason why GPS and Galileo control stations upload an up-to-date version of the satellite's Keplerian orbit parameters, e.g. a and e, usually every two hours.

After locating the satellite in its orbit, the argument of the perigee *w*, the longitude of the ascending node Ω and the inclination of the orbit *i* are used to transform the position of the satellite to ECI using a set of rotations as shown in Figure 6. These parameters are transmitted by GPS and Galileo satellites as part of the ephemeris message.

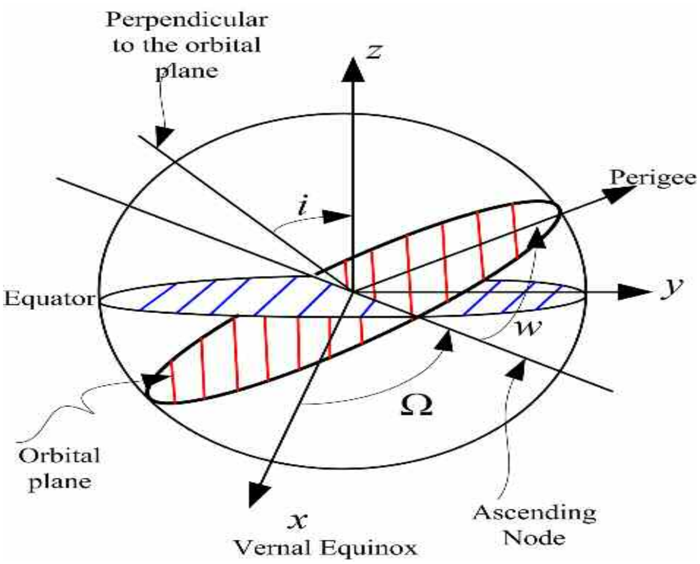

Fig 6 Satellite's position in ECI

GLONASS satellites, on the other hand, do not transmit any Keplerian parameters in the ephemeris of the navigation message. They simply transmit the location and the velocity of the satellite at a specific epoch in ECEF.

Rotating the differential equation (9) from ECI to ECEF and updating it to take into account the spherical harmonics and the gravitational forces of the sun and the moon would allow the UE to estimate the position of the satellite in a time span of 30 minutes around the reference epoch. Fourth-order Runge-Kutta numerical methods are usually used by GLONASS receivers to determine the position of the satellite in a span of 30 minutes based on the motion differential equation and the location and velocity of the satellite in ECEF at the reference epoch. The solar/lunar gravitational accelerations in ECEF are also transmitted as part of the ephemeris of GLONASS satellites.

APPLICATIONS

Different types of GNSS receivers are used, depending on the precision required by the specific application. To understand these applications, it is important first to understand the generic functionality of the different hardware and software modules of a GNSS receiver. The three basic functionalities of a GNSS receiver are described below.

- Acquisition

The receiver uses open loop circuits to search for the Doppler frequency and the approximate code phase for every visible satellite if enough acquisition channels are available in the device. The code phase search window for GPS is 1,023 chips, for GLONASS 511 chips and for Galileo 4,092 chips. These are the lengths of the corresponding spreading code of the respective GNSS. The search resolution is usually ½-chip, which maps to around 150 m in GPS, since the chip rate of the coarse acquisition (CA) civilian signal is 1.023 MHz.

The search window for the Doppler usually has a resolution of 50 Hz. Signals are acquired on a per-channel basis, and the up to ½-chip phase-ambiguous signal is passed to the code and carrier tracking loops to achieve perfect signal locking, thereby removing code-phase and frequency ambiguities.

- Tracking

The code phase acquired from an acquisition channel has a maximum error of ½-chip (150 m in GPS). The code phase is tracked in a delay locked loop (DLL), which utilizes the special correlation properties of GNSS signals to track and lock the code phase. Locking the carrier phase usually happens in a phase locked loop (PLL). The two tracking circuits are interconnected, since the DLL requires that the PLL eliminate the Doppler shift, while the PLL requires that the DLL provide perfect correlation.
Like acquisition, signals are also tracked on a per-channel basis. It would not be possible to track a signal without an acquisition stage that initializes the DLL and PLL, thereby allowing them to converge when tracking the GNSS signal of a specific satellite.

- Navigation

The navigation algorithm makes use of all the CDMA code-phase and carrier-phase readings (depending on the application) to calculate the position of UE.

STANDARD GNSS

Standard GNSS receivers usually operate on one frequency band, the L1/E1 band. GLONASS enhances GPS receivers by increasing the probability to find at least four satellites at a LOS. The precision of standard GNSS receivers is around 10 m.

A-GNSS

The calculation of a satellite position requires decoding the navigation message. It takes 30 s in GPS to decode one frame containing an ephemeris set, and the receiver cannot get a position fix before decoding the first three subframes (18 s) of a GPS page. As a result, it takes a long time to get a location fix when booting a GNSS receiver. Using A-GNSS, a mobile communications downlink such as CDMA2000 transmits the ephemeris navigation information to the UE, thereby minimizing the time needed by the UE to get a fix to around 1 s.

Additionally in the UE-assisted mode of A-GNSS the mobile phone works as a sensor and thus only acquires and tracks code and carrier phases. An assisted server is responsible for locating the UE on the basis of the reported tracking observations from the UE to a base station (BS). The BS, e.g. LTE BS, transmits some acquisition assistant data to the UE prior to the measurement. This data is used by the UE to reduce its code and carrier phase search windows, thereby minimizing the acquisition effort and consequently accelerating the acquisition process of the GNSS sensor.

The acquisition assistant data is simply the acquired code phase and carrier phase or frequency read from a GNSS receiver located at the BS tower. The UE initializes its acquisition code and frequency search windows around the values transmitted by the BS and in this way reduces the size of the acquisition search windows depending on the maximum BS coverage radius.

DIFFERENTIAL GNSS

As expressed in the generic channel equation (3), two of the most significant factors affecting the accuracy of determining the position of a satellite are the ionosphere and satellite clock correction ambiguities.
The vector (baseline) from a static reference point – which is at a close proximity to the user – to the UE can be determined by simply processing the tracking readings or the ionosphere delay as well as the satellite clock error of the static reference point at the UE. This makes it possible to eliminate the similar ambiguities in the ionosphere and satellite clock and thus improve the performance of GNSS to 1 m. The transmitted correction data is called differential data. GNSS performance can increase even more if carrier phase readings are additionally used.

Differential corrections are usually transmitted using regional navigation satellite systems, which are also called satellite-based augmentation systems (SBAS). The best known SBAS is the American WAAS providing D-GPS service to North America.

MULTIPLE FREQUENCY GNSS

Satellites sometimes transmit the same signal on different bands, e.g. GPS on L1 and L2. By combining tracking readings from L1 and L2, it is possible to remove the ionosphere ambiguities. This is because the ionosphere deflection from the LOS is inversely proportional to the square of the carrier frequency. As a result, GNSS performance can be improved to the range of 5 m.

CONCLUSION

Although many advanced applications such as multiple frequency GNSS and differential GNSS can improve the performance of GNSS receivers very significantly, the commercial solutions are still heavily limited to standard GNSS and A-GNSS because they are easy to implement. In the future, the market trend will continue to move toward combining GNSS signals on common bands such as L1/E1 to increase satellite availability in urban areas.

ABBREVIATIONS

A-GNSS	Assisted GNSS
ARNS	Aeronautical radio navigation service
BOC	Binary offset carrier
BS	Base station
CA	Coarse acquisition
CDMA	Code division multiple access
C/N	Carrier-to-noise ratio
CS	Control station
DLL	Delay locked loop
ECEF	Earth-centered, Earth-fixed
ECI	Earth-centered inertial
FDMA	Frequency division multiple access
GNSS	Global navigation satellite system

GPS	Global positioning system
LBS	Location-based services
LOS	Line of sight
MEO	Middle earth orbit
PLL	Phase locked loop
PRN	Pseudo random noise
RNSS	Radio navigation satellite services
SBAS	Satellite-based augmentation system
SV	Space vehicle
UE	User equipment
UTC	Universal time coordinate
UV	Ultraviolet
WAAS	Wide area augmentation system

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[1] B. Hofmann-Wellenhof, H. Lichtenegger and J. Collins, GPS Theory and Practice, Springer-Verlag, 1993.
[2] Elliott Kaplan, Christopher Hegarty, Understanding GPS: Principles and Applications, Artech House, 2006.