1 Methods of positioning with navigation satellites

"It is impossible to achieve theoretical understanding of the universe without instruction"
Claudius Ptolemy, Almagest.

In this book we consider ***Global Navigation Satellite Systems (GNSS)*** and their applications in navigation and geophysics. First established and up until today the main system is the American GPS, followed a little bit later by the Russian GLONASS. Both were created for navigational purposes. In this chapter we consider the principles and methods of navigation with GNSS satellites. We also give some main definitions here, which are used throughout the book.

1.1 Global and regional satellite navigation systems

Satellite navigation systems can be divided into two main categories: global and regional. There are also local systems, which are based on pseudolites. These systems, though not strictly satellite systems, are also considered in this book, because they may be used in conjunction with GNSS or they may use the same type of signal and the same user equipment as GNSS.

Global Navigation Satellite Systems (GNSS) provide global satellite coverage over the Earth and usually use satellites placed on medium Earth orbits (MEO) with an approximate altitude of 20 000 kilometers above the Earth's surface. The revolution period for MEO satellites is about 12 hours. There are two fully operational global navigation satellite systems today. They are: American Global Positioning System (GPS) [1] and Russian **GLO**bal **NA**vigation **S**atellites **S**ystem (GLONASS) [2] or **GLO**bal'naia **NA**vigacionnaia **S**putnikovaia **S**ystema in Russian. The revolution period is about 11 hours 58 minutes for GPS and about 11 hours 16 minutes for GLONASS. European GNSS Galileo and Chinese Beidou (Compass) systems are under development. The main function of these systems is to provide a ***ranging service***. The ranging service from a satellite gives a user an ability to measure distance to the satellite at each moment of time. The satellites may also transmit correction data for their ranging service. The correction data if transmitted are embedded in the satellite signal which is used for the ranging service. Satellite systems can also have secondary functions, which are not related to positioning. These secondary functions are not considered in this book.

1.1.1 GPS

The GPS development started in the mid-seventies as a U.S. Department of Defense (DoD) multi-service program. The GPS was completed in the early nineties and in 1994 had been officially accepted by the US Federal Aviation Administration (FAA) for use in aviation. GPS employs Code Division Multiple Access (CDMA), the same principle which is used today by cellular phone systems. All satellites broadcast their signals on the same frequency but with a different spreading code. The spreading code allows user equipment to acquire the signal, which is below the noise floor, and to distinguish between various satellites. The system is undergoing modernization to implement new signals for the benefit of civilian users and for aviation applications. Some of these new signals are already available.

Since the mid-nineties GPS has enjoyed tremendous success, becoming probably the second most widely applicable technology after the Internet. GPS has helped to create a huge number of jobs worldwide, has revolutionized navigation and geodesy, and has had a major impact on many other areas of science and technology including geophysics, geography, fleet management, travel, and so on. Much of the success of the system is due to the public accessibility of the signals and information about the system, allied to the absence of any royalties and of any hidden fees for a user. In year 2000, removal of accuracy limitations for civilian users also played a huge role in the overall GPS success. All this made GPS an essential and probably main system for any multi-GNSS equipment. This most likely will be the case for many years to come, even when more GNSSs become available.

1.1.2 GLONASS

GLONASS development was started soon after GPS by the former USSR. It was declared operational in 1996. GLONASS employs Frequency Division Multiple Access (FDMA) on top of CDMA. The GLONASS spreading code can be the same for all satellites, because the satellites are distinguished by slightly different frequencies. Though the frequencies for each satellite may be different, the signal structure is similar to GPS, because the spreading code is necessary in order to detect a very low power satellite signal.

FDMA had been implemented in GLONASS probably because the system mostly was envisioned as a military response to GPS by the Soviet Union. FDMA improves system anti-jamming capabilities, because it would require much more power to jam signals on a broader frequency band. However, FDMA also leads to more complicated, bulky, and heavy user equipment, which has an adverse impact on consumer applications. Current levels of radio technology, however, would allow to overcome this shortcoming almost completely. Nowadays, user equipment is becoming not only multi-system but also multi-frequency by definition.

On the other hand, the frequency band for GLONASS has been narrowed. The same frequencies are used for satellites located on different sides of the globe. There is a plan to employ CDMA for new GLONASS signals. Today GLONASS has already started to move to CDMA. A new GLONASS-K satellite started to transmit a CDMA signal in

2011. The new GLONASS-K satellite is based on a non-pressurized platform. Consequently GLONASS-K is smaller and considerably lighter than previous models, allowing use of a wider range of launch vehicles and thus making them less costly to put into orbit. The weight of a GLONASS-K satellite falls to 700 kg instead of the 1415 kg of previous satellites. After the complete constellation is deployed, it will require one Soyuz launch per year to maintain the constellation in full [3]. The estimated service life is significantly increased, and the satellites broadcast a CDMA signal on an additional third civilian L-band frequency. At the same time, the existing legacy FDMA signals are guaranteed to be kept "until the last receiver which uses them stops working" [2].

Under the same conditions, GPS currently provides users with more accurate position estimation than GLONASS, in particular because GLONASS broadcast ephemerides are less accurate. The tracking stations for GLONASS are located regionally rather than globally. The regional tracking station distribution affects the overall potential accuracy of orbit parameter estimation. However, as we show in the next chapter, GLONASS orbits are less affected by irregularities of the Earth's gravitational field, which partly compensates for the regional character of the tracking station network. The difference in accuracy is much less significant in differential mode, when corrections to orbits, clocks, and propagation in the atmosphere are estimated using local reference stations.

Another drawback of FDMA is a necessity to process more data, because a wider frequency band requires a higher sampling rate. This can be compensated for by a trade-off with accuracy.

With a full constellation and new signals, GLONASS today is becoming an attractive and essential component of multi-GNSS equipment worldwide.

1.1.3 Galileo

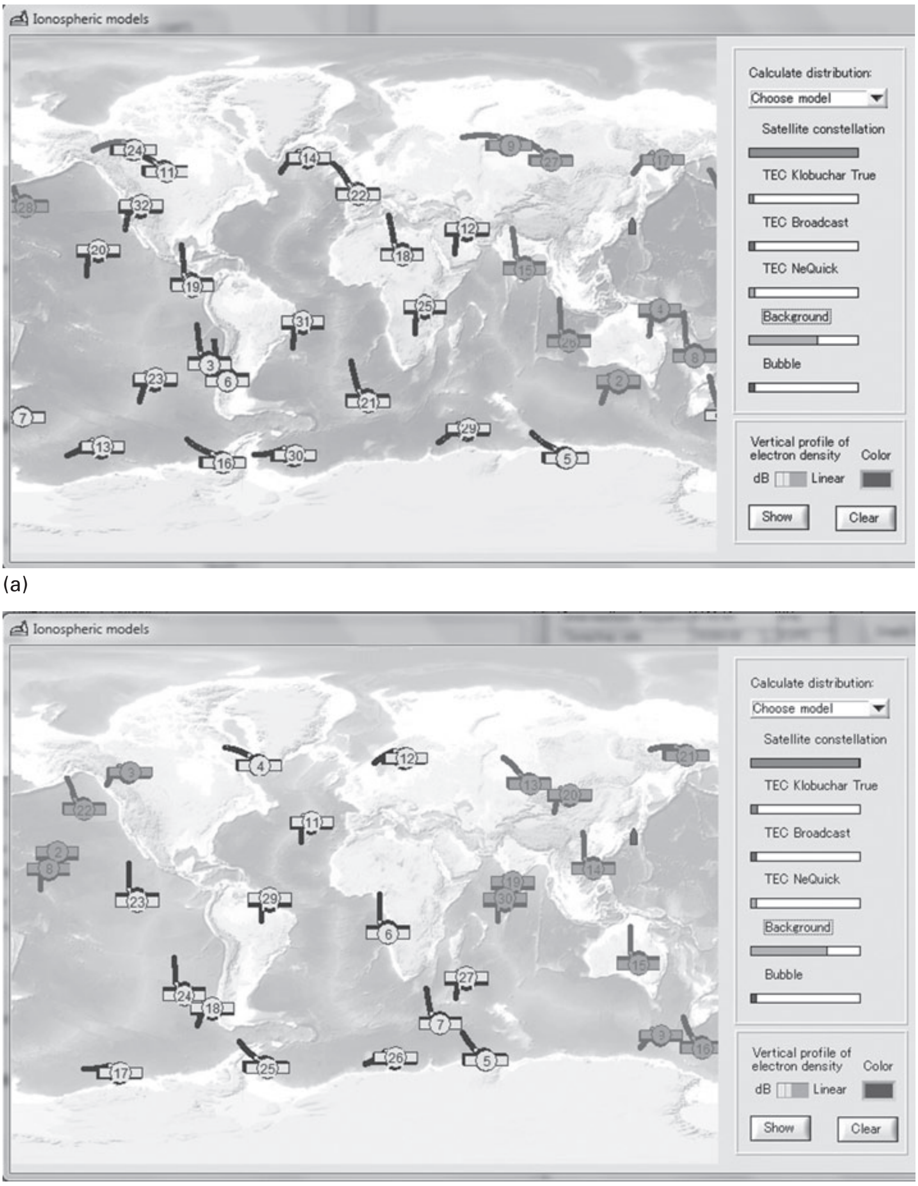
The Galileo development was started recently by the European Union. The Galileo system is also based on CDMA. Many receiver manufacturers are already supporting Galileo signals. With receiver manufacturers tending to move toward software receiver technology it becomes easier to incorporate new signals into existing receiver architecture. In this book we describe software receiver technology based on existing GPS and GLONASS. But the basic principles of GNSS signal generation and reception given here can be easily adapted to the Galileo signals as well as modernized GPS and GLONASS.

We use the ReGen software signal simulator, a free ultra-light version of which is bundled with the book. Figure 1.1 shows satellite distribution over the Earth for GPS and Galileo generated using ReGen software. User position is depicted by a pentagon.

1.1.4 Regional satellite systems

Regional satellite navigation systems provide regional coverage and are usually implemented as geostationary or ***Highly Eccentric Orbit (HEO)*** satellites. The geostationary satellites are located on ***Geo-synchronous Earth Orbit (GEO)*** with altitude of 35 856 kilometers and should keep their position constant relative to the Earth's surface.

The regional systems include American WAAS, Japanese MSAS, Japanese QZSS, European Global Navigation Overlay System (EGNOS), Indian GAGAN (GPS Aided



(a)

(b)

Figure 1.1 GPS (a) and Galileo (b) constellation ground tracks for a one hour interval. ReGen GUI screenshot.

Geo-Augmented Navigation), Chinese Beidou (Compass in Chinese), and Russian Luch (Beam in Russian). The Chinese Compass is designed to combine components from global and regional systems with some satellites on MEO and some on GEO.

The regional systems have three main functions:

1. To provide corrections for global system users in order to improve the ranging service from global systems.

2. To provide system integrity.
3. To provide an additional ranging service.

To provide ***integrity*** means to guarantee that there is a certain time interval within which a user will be notified if there is any fault in GNSS signals which are used for positioning. This interval is set to six seconds for WAAS.

The Russian regional satellite system Luch is going to be introduced with three satellites in GEO. Their designated location is at orbital slot at 16° west longitude (2011), 95° east longitude (2012), and 167° east longitude (2014). The coverage from GEO satellites excludes northern regions. Therefore it is planned to enhance coverage with HEO satellites, in particular using Molniya orbits. The system will also provide an Internet-based service.

1.1.5 GNSS structure

All these systems can be seen as composed of two parts, a ***space segment***, which is a satellite constellation, and a ***ground segment*** (see Figure 1.2). Sometimes a ***user segment*** is also included as a part of the system. A user segment comprises all service users, including those on the surface of the Earth and in space. The ground segment is an essential component and it consists of:

– a network of GNSS tracking stations,
– master clock,
– control center,
– upload facilities.

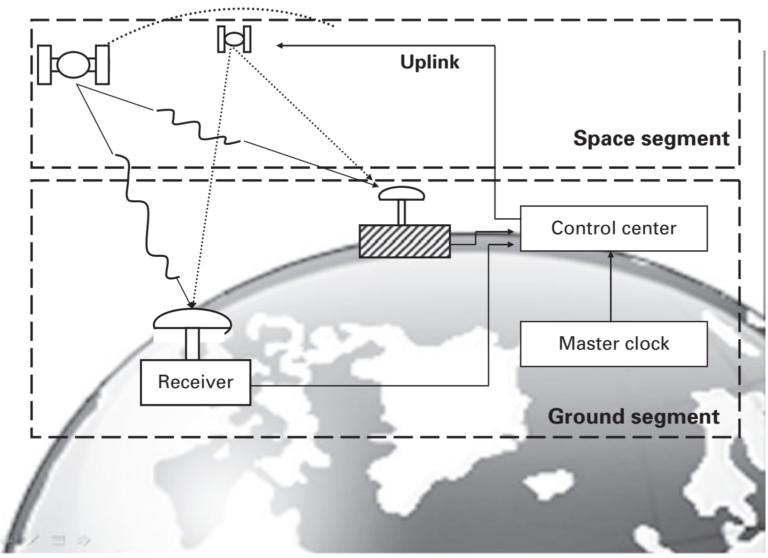


Figure 1.2 GNSS structure.

The ground segment main task as far as positioning is concerned is to define and predict satellite orbits, and upload their parameters to the satellites. The satellites then broadcast their orbit parameters within the satellite navigation message. The ground segment is also a cornerstone of the system control and maintenance. Its essential component is a network of stations, which measure distance to satellites. The distance to a satellite can be measured by using the satellite ranging signal, in which case the station consists of a satellite signal receiver. The distance can also be measured by other means, for example, by measuring a reflected laser signal from a satellite, which is carrying a special mirror for that purpose. This two-way measurement system was first introduced in GLONASS satellites. The satellite orbit measurements can also be augmented by inter-satellite range measurements.

First let us consider what tasks GNSS can solve and what the requirements for these particular tasks are.

1.2 Positioning tasks in navigation and geodesy

Satellite navigation systems solve two primary positioning tasks, which we can roughly describe as being related to areas of navigation and geodesy. These two tasks imply different requirements and therefore different underlying technology.

The ***navigation task*** normally requires sub-meter to meter level accuracy, and instant delivery of the positioning solution, which besides coordinates can also include velocity and attitude information. The solution must be supplied in real time and an initial position fix should be achieved as soon as possible. Specification parameters for navigation solutions usually include accuracy and ***time to first fix (TTFF)***.

TTFF is an important specification for navigation today, especially for hand-held devices. TTFF is normally limited to the time required to receive a complete navigation message from a navigation satellite. This time is equal to 36 seconds in the case of a GPS navigation message. TTFF can be shortened if the satellite orbit parameters and clock data are provided by some other means and reception of the complete navigation message is not required. In this case only a part of the navigation message, which provides a time mark, is required. In the case of GPS, it takes six seconds to receive one frame of the navigation message and ensure that the time mark is received. Of course, it may be received in one second, but the guaranteed time is six seconds. It is possible to resolve time without a navigation message at all, and therefore TTFF can be limited only by the time required for signal acquisition and positioning calculations. In the case of a GPS L1 C/A signal, one millisecond of signal is enough for a positioning fix, if satellite orbits and clock errors are known by the receiver [4]. Another requirement is that the navigation task should be solved as autonomously as possible. It is of course a trade off with TTFF and accuracy.

A ***geodetic task*** on the contrary would benefit from involving as much extra information as possible. This information may include measurements from multiple reference stations for some period of time. Information from other sensors related to the state of the ionosphere and troposphere can also be used in order to mitigate atmospheric effects on signal propagation. The geodetic task is normally solved in post-processing. The requirements for coordinate accuracy level are much higher and generally on the level of millimeters. The geodetic task may also include finding of various geodetic and physical parameters, such as Earth orientation parameters, atmospheric parameters, and so on.

Until recently there were two distinctive streams of applications related to these tasks. These streams were developing relatively independently. The navigation stream probably began together with human history. However, until the seventeenth century navigation was always based on integration with dead reckoning systems. Only in the seventeenth century did it become possible to define coordinates without dead reckoning. Prior to that the coordinates where derived only by dead reckoning and people were defining a position in relation to the starting point. Geodesy abandoned dead reckoning even later. At some point both geodesy and navigation began to use GNSS as a major tool, though the methods, algorithms, and user equipment in applications were quite different. Recently these two streams have come very close and it is no longer possible to learn about one without learning about the other. Geodetic features have become available for real-time applications, and navigation tasks have come closer to geodetic accuracy level [4].

One of the two main subjects of this book is to solve a positioning task with GNSS. We define ***positioning with navigation satellites in a wide sense*** as a task of finding object coordinates, linear and angular, and their derivatives. The coordinates also include time. We can consider an object either as a body or as a point mass. If we consider the object as a body, then coordinates include angular coordinates and their derivatives. If we consider the object as a point mass, then only linear coordinates and their derivatives are included in the positioning task. Three linear coordinates are required to describe an object position as a point mass in a coordinate frame in a three-dimensional world. Six coordinates are required to describe an object as a body in a three-dimensional coordinate frame at a specific instant of time, which is called an ***epoch***. In satellite navigation, whether or not an object is dynamic, it is always required to consider its position in a time-frame as well. Therefore, time variable and coordinate derivatives must always be considered.

It is important that the same object can often be described either as a point mass or a body depending on the specific task. In a navigation task, for example, a navigation satellite is considered as a point mass, whereas in geodesy, the satellite is considered as a body in order for a model to account, for example, for solar pressure.

We define ***positioning with satellite navigation in a narrow sense*** as a process of finding three coordinates of a receiver's antenna phase center. An antenna phase center is a mathematical abstraction and as such is always a point mass. Note that user coordinates are always in fact coordinates of the user receiver antenna phase center. It means that if we have a user with a receiver located in one place and the receiver antenna located at some distance from the receiver, for example at a few kilometers distance connected to the receiver by fiber optical cable, then the user will be measuring the coordinates of the antenna phase center. The coordinates will be calculated without any extra errors caused by the cable, besides those caused by power loss in the cable and a sequentially lower signal to noise ratio. Such systems can be used, for example, for landslide monitoring and in other hazardous environments. In this case only antennas are located in the hazardous environment, whereas all other monitoring equipment, including the receiver, can be located at the safe place [5].

It is also important to note that the antenna phase center depends on the direction from which a satellite signal comes. The antenna phase center may vary as a function of satellite elevation and azimuth. High-end geodetic antennas are calibrated and have elevation-dependent phase center corrections, which should be accounted for when high accuracy is required. Neglecting this effect may account for up to 10 cm error in height [6].

Coordinates describe an object's position in a certain coordinate system, and a coordinate system comprises a reference coordinate system and timeframe.

1.3 Reference coordinate systems

We can define coordinates only in relation to a specific reference coordinate system. The choice of coordinate system affects the accuracy of our coordinates and convenience of their usage. A GNSS user defines position in a coordinate system fixed to the Earth and rotating with it. These ***Earth centered, Earth fixed (ECEF)*** coordinates can be defined by a network of GNSS tracking stations, and therefore can also include the GNSS constellation as part of their definition. That is so far as the navigation task goes. For geodetic tasks, however, we have to consider that these GNSS tracking stations do not comprise a rigid structure on the millimeter level of accuracy. The coordinate system is constantly breathing. An ECEF is then related to fixed stars, which define an inertial coordinate system. However, the inertial system as far as it can be defined is also slowly moving. Main reference coordinate systems are given as described below.

1.3.1 Earth centered inertial (ECI) frame

An ***Earth centered inertial (ECI)*** coordinate frame (see Figure 1.3) is a Cartesian coordinate frame with an origin placed in the Earth's center of mass, and axes fixed relative to the stars. The Z axis coincides with Earth's spin axis and the X axis is defined by the direction from the Earth to the Sun on the first day of spring, when the Sun crosses the Earth's equatorial plane. This point of intersection between the Sun trajectory (ecliptic) and the Earth's equatorial plane is called the ***vernal equinox*** or First Point of Aries. The second name comes from the time of naming, thousands of years ago, when the vernal equinox was in the zodiacal constellation the Ram (Aries). The Aries zodiacal symbol ♈ is still used to mark the vernal equinox.

There are several ECI realizations. The ***International Celestial Reference Frame (ICRF)*** is realized by a catalogue of extragalactic stars based on very long baseline interference (VLBI) observations.

The vernal equinox is moving; therefore it is apparent that the ECI is also moving relative to the stars. This vernal equinox precession has a period of 26 000 years, which results in an ECI precession rate of 0.014° per year. This drift makes it necessary to

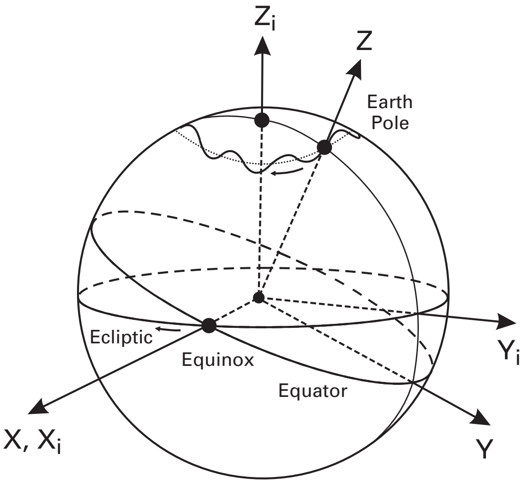


Figure 1.3 Earth centered inertial (ECI) coordinate frame.

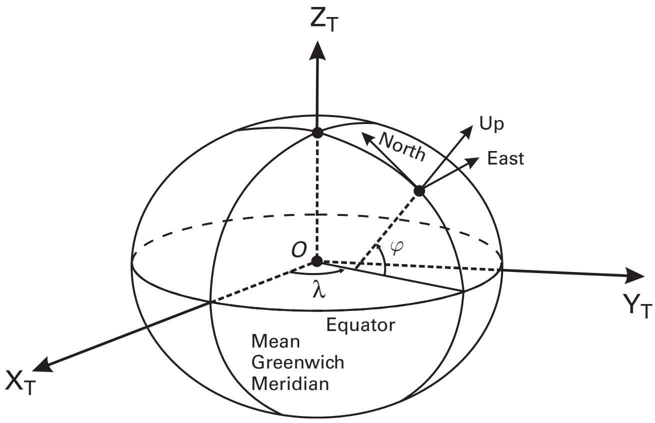


Figure 1.4 Earth centered, Earth fixed (ECEF) coordinate frame and topocentric horizon frame.

reference coordinate frames to a certain date. For example, the European CODE (Centre for Orbit Determination in Europe) – Analysis Center for the International GNSS Service (IGS) – uses the system J2000.0. The vernal equinox coordinates are then adjusted to the epoch of interest through precession and nutation transformations, which are given as sequences of rotations [7].

1.3.2 Earth centered, Earth fixed (ECEF)

The ECEF is a Cartesian coordinate frame with an origin placed in the Earth's center of mass. The Z axis coincides with Earth's spin axis, the X axis goes through the Greenwich meridian. The ECEF is rotating with Earth (see Figure 1.4).

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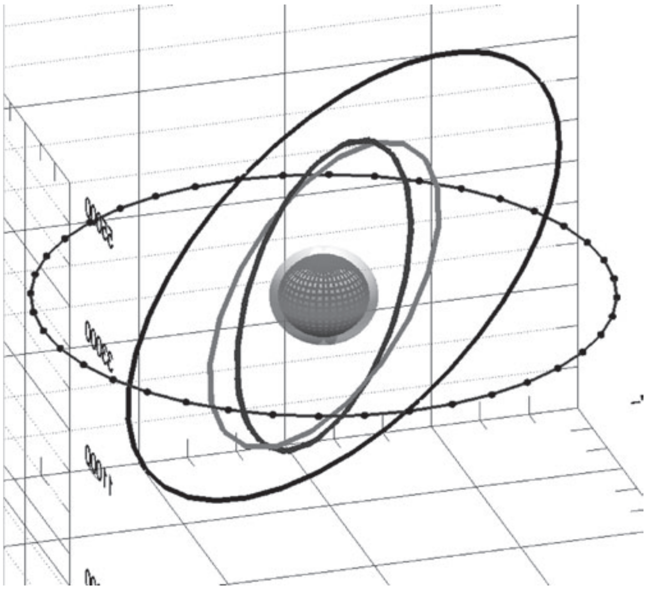

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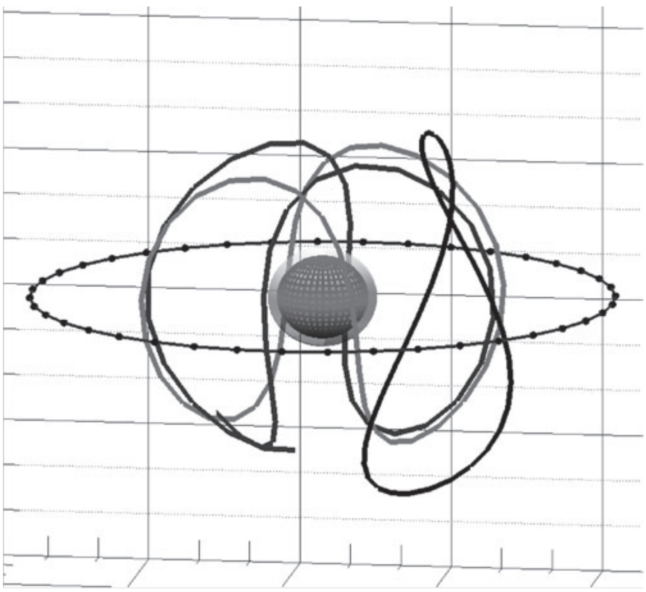

(b)

Figure 1.5 GPS, GLONASS, GEO, and QZSS orbits in ECI (a) and ECEF (b). ReGen GUI screenshot.

The satellite orbit parameters are given in one of the ECEF systems. That is convenient because they are defined in the ECEF of the tracking network. The satellite orbit parameters are considered in the inertial frame, because an orbit mathematical presentation in the inertial frame is much simpler, as we can see from Figure 1.5. In order to be