Chapter 4

GNSS Error Sources

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Additional information is available at the end of the chapter

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Abstract

This chapter discusses the most serious sources of error affecting global navigation satellite systems (GNSS) signals, classifying these in a new way, according to their nature and/or effects. For instance, errors due to clock bias or drift are grouped together. Errors related to the signal propagation medium, too, are treated in the same way. GNSS errors need to be corrected to achieve accepted positioning and navigational accuracy. We provide a theoretical description for each source, supporting these with diagrams and analytical figures where possible. Some common metrics to measure the magnitude of GNSS errors, including the user equivalent range error (UERE) and the dilution of precision (DOP), are also presented. The chapter concludes with remarks on the significance of the sources of error.

Keywords: GNSS, errors, ionosphere, troposphere, multipath, clock, jamming, noise

1. Introduction

The services provided by global navigation satellite systems (GNSS) are used in a massive number of applications, both civilian and military. All GNSS systems comprise many satellites orbiting the Earth at very high elevations. At a single point in time, there will be several satellites from which a receiver may have a clear line of sight to receive signals and build its own navigation solution. However, these signals are prone to several sources of disturbance, causing errors in the measurements that are generated inside the receiver, which in turn degrades positioning accuracy.

Most of the discussions here apply to all GNSS systems, but in some instances, we use the US GNSS system—the Global Positioning System (GPS)—as an example to explain our ideas.

Figure 1 depicts the structure of a typical GNSS system—GPS—with its three primary segments. In all GNSS systems, the signal makes a journey of thousands of kilometers between the satellite antenna and its destination, the receiver. The first and longest part of this trip is through space where the signal attains its characteristics. Nonetheless, when the signal travels through the atmosphere, this medium imposes some undesirable effects. The layers of the atmosphere add delays to signal propagation time, causing some errors in the measurements.

Once the signal nears the receiver antenna, it usually experiences some reflections and echoes, i.e. the signal often bounces off objects surrounding the receiver, potentially hitting the antenna multiple times—this phenomenon is known as multipath. Multipath is one of the major error sources that can be very harmful to GNSS signals in many applications [1]. All the abovementioned signal disturbances result from the nature of the signal or the propagation medium and are unintentional. Intentional signal degradation or replacement could be in many cases a tougher source of GNSS errors. One major type of deliberate errors is signal jamming. Signal jamming is deliberate interference caused by the broadcasting of radio frequency (RF) signals near the receiver with the aim of preventing the tracking of GNSS signals. Some other less harmful error sources are discussed in this chapter, including system (circuit) errors and satellite orbital errors.

In general, this chapter discusses thoroughly the major sources of GNSS error sources, their causes, consequences, and scales. Each error source or factor is explained in depth, with supporting figures whenever possible. Another contribution of this chapter is the presentation of a new scheme for categorizing GNSS errors.

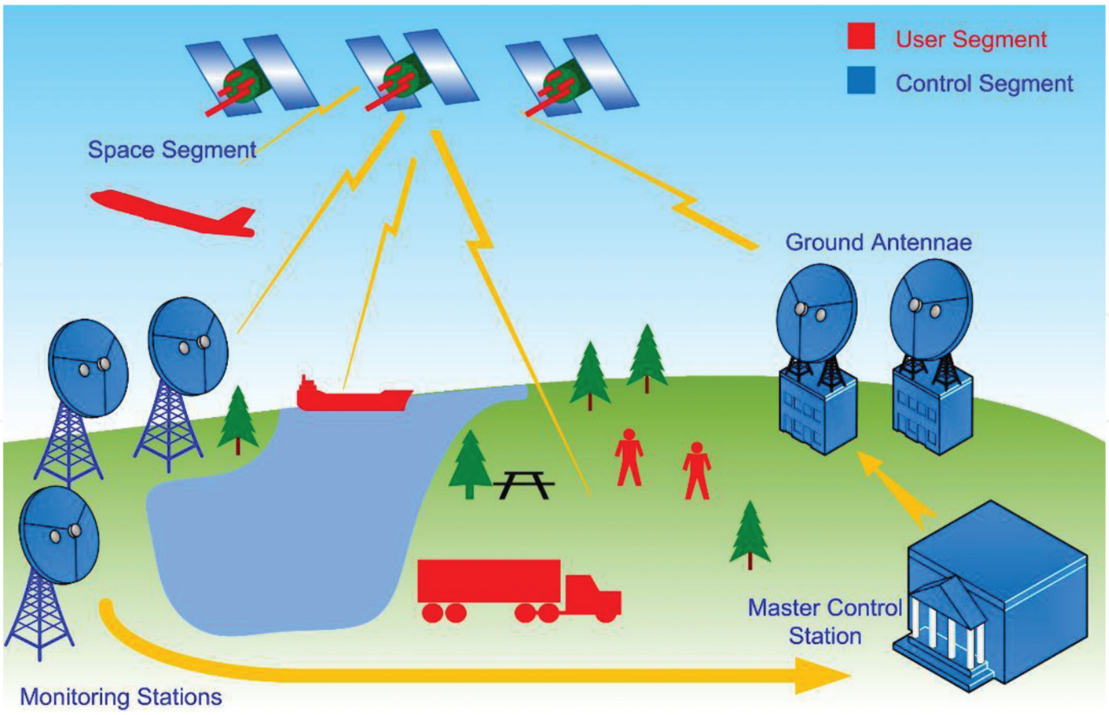

Figure 1. The three GPS segments. Courtesy of Noureldin et al. [2].

It is worth mentioning that in this work, we address the error sources that affect the standard point positioning (SPP) accuracy level where the receiver uses the broadcast ephemeris information and single-frequency measurements to estimate its position with a meter-level accuracy. However, there are other error sources that affect accuracy within the centimeter and millimeter level such as antenna phase center, phase wind-up, and site displacement errors. To achieve this degree of accuracy, the receiver needs to work in either differential GNSS mode or precise point positioning (PPP) mode, both of which are beyond the scope of this chapter.

2. Error sources and consequences

GNSS signals have very low power, and hence they are prone to several sources of noise and errors. The range measured by the GNSS receiver is contaminated by these errors, which is why it is called the *pseudorange*. The general pseudorange observation equation is expressed as follows:

$$P_r^s = \rho_r^s + c\left(dt_r - dT^s\right) + I_r^s + T_r^s + \varepsilon_r^s \quad (1)$$

where P_r^s is the pseudorange between the satellite s and the receiver r. ρ_r^s is the true geometric range, c is the speed of light, and dt_r and dT^s represent the receiver and satellite clock errors in seconds. The symbol I denotes the ionospheric delay, while T is the tropospheric delay in meters. Finally, ε combines the multipath and receiver noise errors.

In this section, GNSS errors will be categorized based on the nature of the error itself. Timing-related errors in both the satellite and receiver are grouped as clock-related errors. Signal propagation errors combine atmospheric errors, multipath errors, and the effect of the relative motion between the satellite and receiver. Satellite orbit parameters needed to calculate satellite position and velocity are estimated at the control segment. These parameters are sent to GNSS satellites to be broadcast in the navigation message. This estimation error is combined with the receiver noise effect as system errors. The last type of GNSS error is intentional errors. Those errors are, however, deliberate and can be harmful; these include signal jamming and spoofing.

2.1. Clock-related errors

Receivers generate measurements based mainly on measuring time [3]. Indeed, time is central to GNSS systems; therefore, GNSS satellites are equipped with very precise, and hence very expensive, clocks [4]. Despite their accuracy, satellite clocks still drift slightly from GNSS time. For reasons of affordability and size, receiver clocks are usually much cheaper; consequently, they drift from GNSS time rapidly. This drift translates into dramatic range errors in receiver measurements. Accordingly, it is significant to correct or compensate for timing errors in the GNSS signal. These clock errors can be summarized as follows:

2.1.1. Satellite clock errors

There are three factors that can affect GNSS satellite clocks: stability, relativistic effects, and timing group delay.

Clock stability: The stability of a satellite clock is about 1 to 2 parts in 10^{13} a day, which is approximately 8.64 to 17.28 ns a day. This is equivalent to a range error of about 2.59 m to 5.18 m [5]. This instability $dT^{s'}$ is modeled using the quadratic function:

$$dT^{s'} = a_{f0} + a_{f1}(t - t_{oc}) + a_{f2}\,(t - t_{oc})^2 \tag{2}$$

where t is the receiver GPS time, t_{oc} is the reference epoch time, a_{f0} is the clock offset, a_{f1} is the clock drift coefficient, and a_{f2} is the clock drift rate coefficient. The values of t_{oc}, a_{f0}, a_{f1}, and a_{f2} are obtained from the broadcasted navigation message.

Relativistic effects: A clock aboard a satellite will be affected by both the general and special relativity theories. The net result is that this clock will appear to run faster than the same clock on Earth by approximately 38.4 μs/day. Scaled by the speed of light, this is equivalent to a range error of about 11,512 m. To compensate for this effect, a proper offset is introduced to the satellite clock rate before launching [4]. However, there is still a residual effect because of the noncircular satellite orbit, which should be compensated for at the user side. This relativistic correction Δt_r is calculated by [6].

$$\Delta t_r = -\frac{2}{c^2}\sqrt{\mu a}(e\sin E) \tag{3}$$

where c is the speed of light, $\mu = 3.986005 \times 10^{14}$ m^3/s^2 is the Earth's universal gravitational parameter for GPS, a is the Earth's semimajor axis, e is the eccentricity of the satellite orbit, and E is the eccentric anomaly of the satellite orbit. If the orbit was a perfect circle, this effect is zero as the eccentricity is zero. For instance, for an eccentricity of 0.015, the maximum value will be 16.8 ns, which corresponds to around 5 m. Another alternative equation to Eq. (3) is to use the satellite position and velocity to calculate the relativistic correction using the following formula [7]:

$$\Delta t_r = -\frac{2\,\mathbf{r}^s \cdot \mathbf{v}^s}{c^2} \tag{4}$$

where $\mathbf{r}^s.\mathbf{v}^s$ is the dot product of the satellite position and velocity vectors.

Timing group delay (TGD): the satellite clock corrections in the navigation message are referred to one GNSS signal or signal combination. In the case of GPS, this signal is the ionospheric-free combination of the codes at L1 and L2 frequency bands. In the case of a single-frequency operation, a correction should be made to compensate for the bias offset between L1 and the ionospheric-free combination signals. This correction is also provided in the navigation message, named as timing group delay (TGD) [7].

The total satellite clock error is now calculated by the sum of the three terms as

$$dT^s = dT^{s'} + \Delta t_r + TGD \tag{5}$$

2.1.2. Receiver clock errors

GNSS receivers are equipped with inexpensive crystal clocks, which have low accuracy compared to satellite clocks [8]. As a result, the receiver clock error is much larger than that of the GNSS satellite clock. There are two ways to fix this issue. One is to use external precise, usually cesium or rubidium, clocks which have superior performance, but the problem is that they are very expensive, as they cost between a few thousand dollars to about $20,000 [4].

The other solution, which is much more common, is to remove this error through differencing between satellites or by estimating the error as an additional unknown parameter in the position estimation process. This latter solution is meant to make receiver prices affordable [2]. Adding the receiver clock bias to the set of unknowns, in addition to three position parameters, sets the limitation to a minimum of four visible satellites, instead of three, for obtaining a solution from the receiver.

To prevent the receiver clock error from becoming too large, receiver manufacturers apply a clock-steering mechanism. Two main approaches are used for this [9]. The first method is continuous steering to keep the clock error within the acceptable range. The other method is clock jumping, where clock bias is adjusted only when the error reaches a certain threshold. Although the clock bias is estimated as an unknown parameter in the estimation filter, it should still be kept within a certain limit. The reason for this is that the receiver clock is used to time tag the receiver output. This time tag must have a minimum level of accuracy for time synchronization between different systems to occur.

2.1.3. Intersystem biases

One way to enhance the accuracy and the availability of the GNSS receiver solution is to use all the observations from all available GNSS constellations. GPS and the Russian global navigation satellite system, GLONASS, are currently fully operational systems with global coverage, while other systems are now evolving to achieve the worldwide coverage such as the European Galileo and the Chinese BeiDuo systems.

Each GNSS has its own timing system, and hence, there are some intersystem clock biases that should be considered when dealing with a multi-constellation system. This can be achieved by introducing new unknowns, which represent the time difference between the added GNSS constellation time and GPS time [10]. For example, if GLONASS measurements are to be used, then the receiver clock bias in Eq. (1) can now be represented as $dt_r = dt_{r,GPS} + dt_{r,GPS-GLONASS}$. As the number of unknowns is increased to five, this will require a minimum of five visible satellites from both constellations.

2.2. Signal propagation errors

During signal propagation time, the Earth would have rotated, causing a relative shift between the satellite and receiver locations at signal transmission time and signal reception time. If not accounted for, this relative distance, known as the Sagnac effect, will cause an extra error in the measured range.

Furthermore, the GNSS signal travels a long trip between the satellite and the receiver. The first and longest part of the GNSS signal journey is through space where the signal preserves its original characteristics, foremost of which is its constant speed. At lower altitudes, however, the signal will experience some disturbances, e.g., ionosphere and troposphere effects. Moreover, during the final part of the signal path, the GNSS signal arrives directly at the receiver or via single or multiple reflections from the surrounding objects. This multipath effect is not deterministic and can degrade the signal dramatically. This section covers the factors that affect the signal throughout its journey between the satellite and the receiver.

2.2.1. Sagnac effect

The Sagnac effect is a relativistic error caused by the Earth's rotation during signal propagation time between the satellite and the receiver [11]. Ephemeris parameters obtained from the navigation message provide information about the satellite position expressed in the Earth-centered Earth-fixed (ECEF) frame at signal transmission time. However, during signal transit time, the Earth would have rotated (see **Figure 2**) and, hence, the ECEF frame; consequently, a correction is needed to express the satellite position in the ECEF frame at signal reception time instead of transmission time [2]. The amount of frame rotation during the signal transit time is $w_e(t_r\text{-}t_t)$, where w_e is the Earth rotation rate, t_r is the signal reception time, and t_t is the signal transmission time.

Although this error is not directly observable in Eq. (1), it is inherent in calculating the geometric range ρ_r^s. The geometric range is calculated as the difference between the receiver position and the satellites' position, and by adding the Sagnac correction, it can be written as

$$\rho_r^s = \left\| \boldsymbol{r}_r(t_r) - R_z(w_e(t_r - t_t)) \cdot \boldsymbol{r}_s(t_t) \right\| \tag{6}$$

where $\boldsymbol{r}_{\mathbf{r}}$ is the receiver position vector and $\boldsymbol{r}_{\mathbf{s}}$ is the satellite position vector, both in ECEF frame. $\|\cdot\|$ is the norm, operator and $R_z(\theta)$ is the coordinate rotation matrix around the z-axis of ECEF frame by an angle θ which is defined as

$$R_z(\theta) = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{7}$$

If left uncompensated for, this effect could cause a position error of about 30 m [12].

2.2.2. Ionosphere errors

When the signal reaches an altitude of about 1000 km above the Earth's surface, it penetrates the upper layer of the atmosphere, namely, the ionosphere (see **Figure 3**). This layer of atmosphere includes various types of gases that are readily ionized by the sun's radiation [4]. The intensity of solar activity is the key factor determining the condition of the ionosphere, but it is also affected by season and time of day. Accordingly, these three parameters define the level of ionization, thereby changing the refractive indices of the layers of the ionosphere, therefore, influencing the signal transit time measured by the receiver [8].

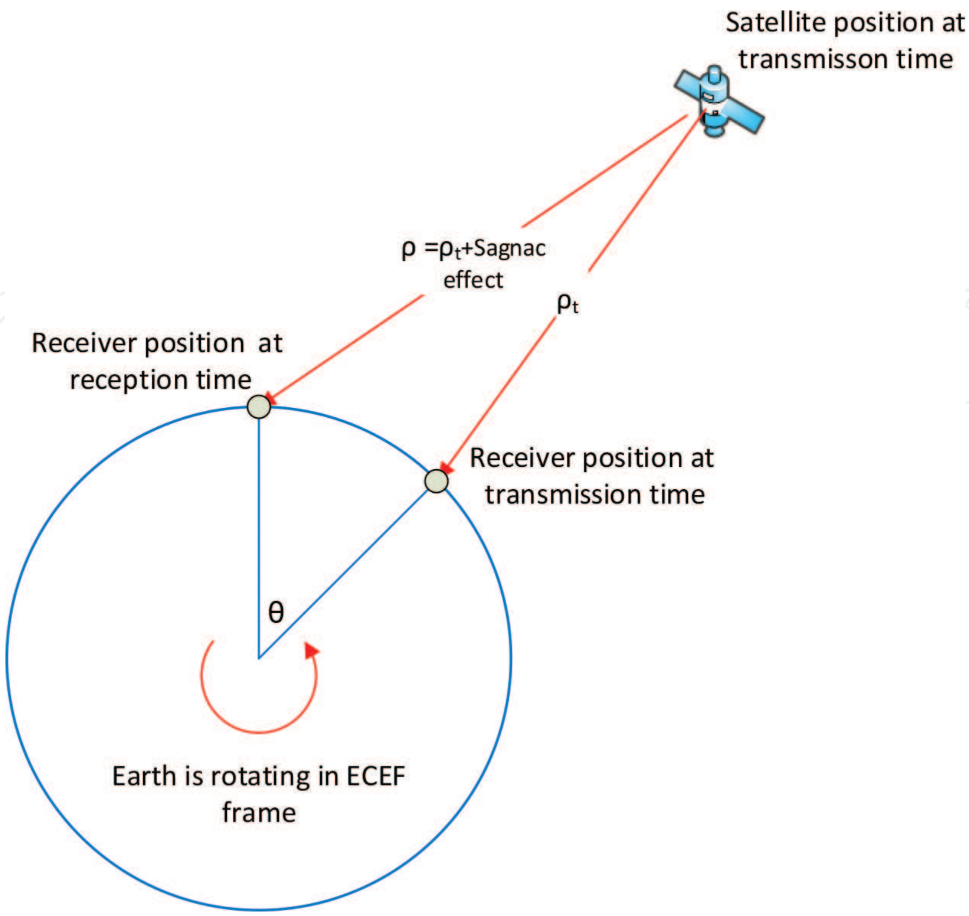

Figure 2. The Sagnac effect.

The ionosphere acts as a dispersive medium, meaning that the ionospheric delay is frequency dependent. This delay represents one of the significant ranging errors in GNSS positioning and can reach a value of 300 ns (100 m) in some situations [13]. The first-order ionospheric delay I, in meters, is represented by the equation:

$$I = \frac{40.3 \cdot TEC}{f^2} \tag{8}$$

where TEC is the total electron content which is defined as the number of electrons in a tube of 1 m^2 cross section in the signal propagation direction and f is the signal frequency.

For dual-frequency receivers, using the ionospheric-free signal combinations, this first-order error can be removed and with it 99.99% of the ionospheric delay [14]. On the other hand, in single-frequency receivers, the ionospheric delay must be modeled or estimated. The simplest way is to use the broadcast models transmitted in the satellite navigation message, such as GPS Klobuchar model [13] and Galileo NeQuick model [15]. Nevertheless, these models can correct for approximately 50% rms of the ionospheric error; even the most accurate theoretical model can only correct up to 80% of this error [13].

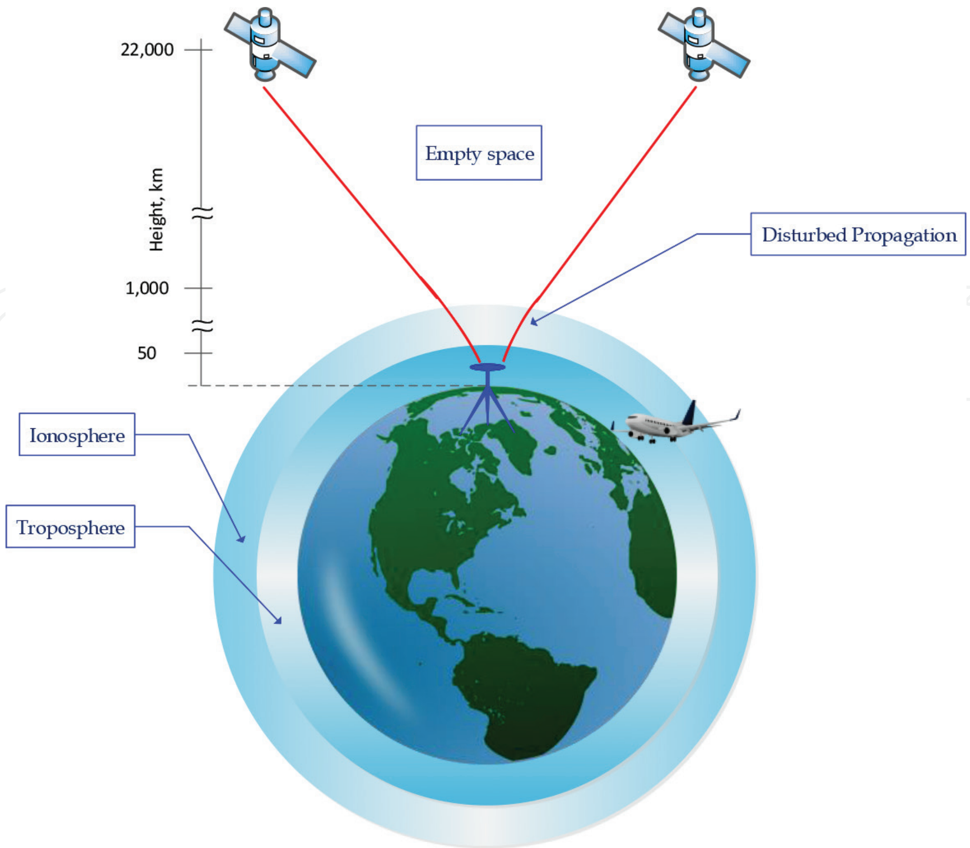

Figure 3. The GPS signal's propagation mediums [18].

The other approach is to use a network of global or local dual-frequency receivers to estimate ionospheric corrections in a grid model. This network usually estimates the vertical TEC (VTEC) and sends these corrections to the users. The satellite-based augmentation network (SBAS) corrections provided by the American Wide Area Augmentation System (WAAS) are an example of such corrections. The VTEC can be used to obtain the total slant TEC through an obliquity factor that accounts for the effect of the satellite elevation angle [16]. If the single-frequency receiver has the capability of receiving these corrections, ionospheric error modeling will be more accurate than using broadcast models.

2.2.3. Troposphere errors

The next step is for the signal to move through the troposphere, the lowest part of the atmosphere, extending from the Earth's surface up to a maximum height of 20 km above sea level (see **Figure 3**). This part of the atmosphere is composed of dry gases and water vapor [16]. Since it is a refractive layer, the troposphere, too, delays GNSS signals; however, being electrically neutral, this layer is nondispersive for some GNSS frequencies [10]. The tropospheric delay has two components: wet and dry. The wet one is difficult to model, but luckily, it accounts for only 10 percent of the delay. The dry one, which is responsible for the rest of the delay, can be more easily modeled. The tropospheric delay is frequency independent; therefore, unlike

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the ionospheric delay, it cannot be removed by combining measurements from L1 and L2 GPS signals. Depending on satellite elevation, the tropospheric delay adds up about 2.5 m to 25 m to range measurements [4].

For meter-level accuracy, several models can be used to mitigate the total tropospheric error, such as Hopfield model and Saastamoinen model. These models usually calculate the zenith delay (for elevation angle = 0) and then use a mapping function to obtain the total slant delay, depending on the satellite elevation angle [17]. For applications that need a higher level of accuracy in tropospheric error estimation, the dry component is modeled, while the zenith wet component is estimated as an additional unknown in the navigation filter.

2.2.4. Multipath errors

As the signal nears the receiver antenna, it can often be further degraded. In several scenarios, the signal may reach the receiver's antenna via more than one path (see **Figure 4**), owing to signal reflections from surrounding structures or the ground [19]. Usually, one of the received signals would be the direct line-of-sight (LOS) signal, along with one or more of its echoes, which are delayed versions of the original signal. Those delayed versions are superimposed on the LOS signal, which can significantly distort the desired LOS signal. The multipath effect depends on the surrounding environment and the relative satellite-receiver motion. Moreover, in general, this effect cannot be canceled through differential positioning—even for closely spaced receivers. Therefore, the multipath error can limit positioning accuracy even if the other error sources have been removed. In the most severe conditions, the multipath error can cause a pseudorange error of up to 100 m [3].

One solution to avoid this source of error is to place the receiver antenna in a reflection-free location; however, this is not always practical, particularly when the GNSS receiver is on a moving platform. Another way to mitigate multipath error is through the receiver or antenna design. The "choke ring" antenna is one of the best-known antennas that mitigates multipath [20]. Other designs were made to keep the same high performance of the "choke ring" with lighter weight and smaller size [21]. Some modern receivers use techniques relying on multiple antennas or what is known as an antenna array. With such technology, the receiver can tune itself to track only the LOS signal and block all other replicas of the signal [22]. The multipath effect can also be mitigated at the measurement level while processing data. The simple way is by weighting the measurements according to the elevation angle, since the multipath error increases at lower elevation angles [1]. A more advanced approach is to detect the multipath effect using code-phase information, such as the code minus carrier observation. This data can be used to adjust satellite weighting or even to reject some measurements with severe multipath effects [23].

2.3. System errors

Some GNSS errors result from the overall nature of the system, e.g., the shape of orbital planes and receiver structure. These error sources are discussed in this section.

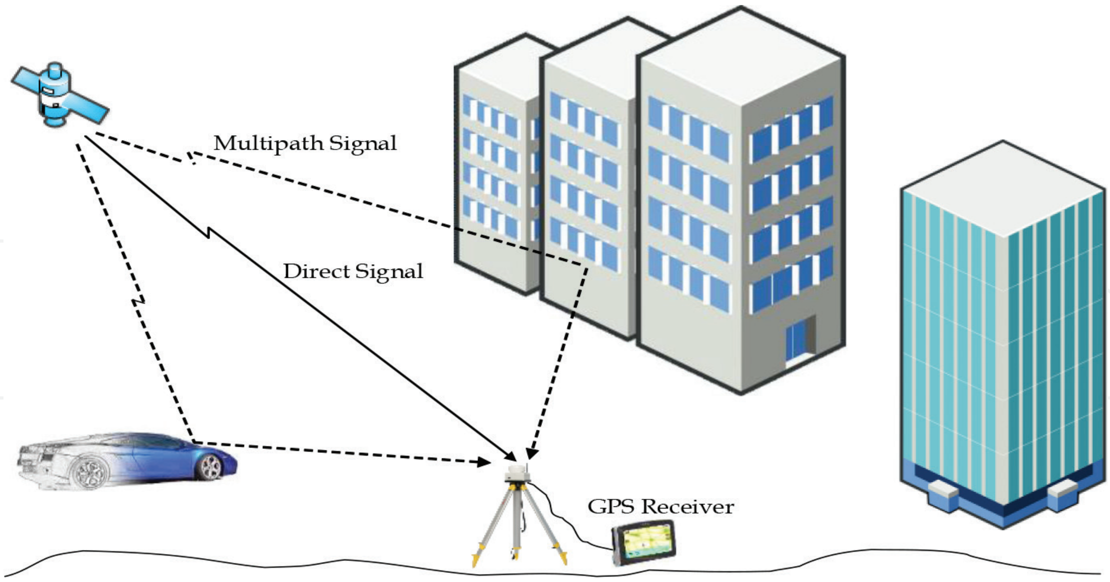

Figure 4. Line-of-sight (direct) and multipath (indirect) signals [18].

2.3.1. Satellite orbital errors

Receivers calculate satellite position based on information contained in the navigation message known as satellite ephemeris. These ephemeris parameters are estimated at the control segment and then uploaded to satellites. Satellites broadcast updated ephemeris data every 2 hours; however, these parameters are estimated using a curve fit to predict the satellite orbit, which leaves residual errors relative to the actual orbit [2]. This error source introduces a root mean square (RMS) error of about 2 m [4]. This error can be mitigated if global or local network corrections for the satellite position are available. These corrections are used to refine the broadcast ephemeris corrections and, hence, improve accuracy. For post-processing, a more precise ephemeris, available from IGS [24], can be used if centimeter-level precision is required and a dual-frequency receiver was used.

2.3.2. Receiver noise

Receiver noise is a complex error generated at the receiver's side while measuring satellite signals. It covers a broad spectrum of noise types, including but not limited to microwave radiations sensed by the antenna in the band of interest unrelated to the signal; noise introduced by system components such as the antenna, cables, and amplifiers; and signal quantization noise [25]. Receiver noise is considered white noise; therefore, it cannot be avoided entirely. However, with modern receiver technology, this term is lessened to about 0.1–1% of a cycle in the carrier phase and d of centimeters in pseudorange measurements. The contradiction here is that receiver noise increases by $\sqrt{2}$ for single-differenced observations, while double-differenced ones have a noise amplification of two [26]. Observation differencing is sometimes used to cancel the common between-receiver errors, between- satellite errors, or both.

2.4. Intentional error sources

Some GNSS error sources are deliberate, i.e., imposed by the service provider or an attack on the system. These are discussed in the following subsections.

2.4.1. Selective availability

Selective availability is associated with only the GPS system among all the GNSS systems. Selective availability (SA) was an intentional degradation of GPS performance by the US government for national security reasons. Satellite clock corrections in the broadcast ephemeris were deliberately degraded to reduce the accuracy for civilian use of GPS to an accuracy level of 100 m for the horizontal position [20]. However, on 2 May 2000, this feature was discontinued, and the USA announced that it would no longer impose this. Furthermore, the new generation of GPS satellites (GPS III) will not have this feature, meaning that SA cannot be used by the US government anymore [27].

2.4.2. Signal jamming

Intentional interference is, in many cases, a significant source of GNSS signal degradation. Intentional interference, known as signal jamming, is caused by the broadcast of malicious radio frequency (RF) signals to prevent GNSS receivers in the area from tracking GNSS signals [11]. The typical direct consequences of jamming are signal frequency shifts in Hertz (Hz) and a drop in signal power in decibels (dB). These effects, in turn, have the potential to cause severe errors in position, velocity, and time calculations and even completely freeze the receiver causing a denial of service condition. Attacking a GNSS signal through jamming requires neither sophisticated knowledge nor complex equipment: all that is needed is a signal of a higher power in the same frequency to defeat the target signal [28]. **Figure 5** shows the visibility of several satellites in an open sky simulation scenario. **Figure 6**, on the other hand, shows the discontinuity (the highlighted rectangle) in satellite availability for the same scenario but when a jamming signal is inserted. The jamming signal lasted for about 1 minute with a power of around −70 dBm and a bandwidth of 10 MHz around the central GPS L1 signal frequency. A slightly higher power jamming signal can completely block signals from all satellites in view.

One option to fight this problem is to use the military (M-Code) receivers or multi-constellation receivers. Another option is to completely switch to any other available navigation solutions [29]. Among these is the long-range navigation system (Loran-C) which is not active now, but there is a noteworthy argument by the US Department of Defense to reactivate it for its significance as an alternative for GPS-based navigation. Furthermore, a modernized version of the system, known as enhanced Loran (e-Loran-C), has been already established and tested. What is special about this system is that its signal power is about a thousand times greater than the GPS signal power. Moreover, it uses an entirely different frequency range from GPS. This makes it safe from the intentional GPS jamming signals. Another alternative is the satellite-based augmentation systems (SBAS) and ground-based augmentation systems

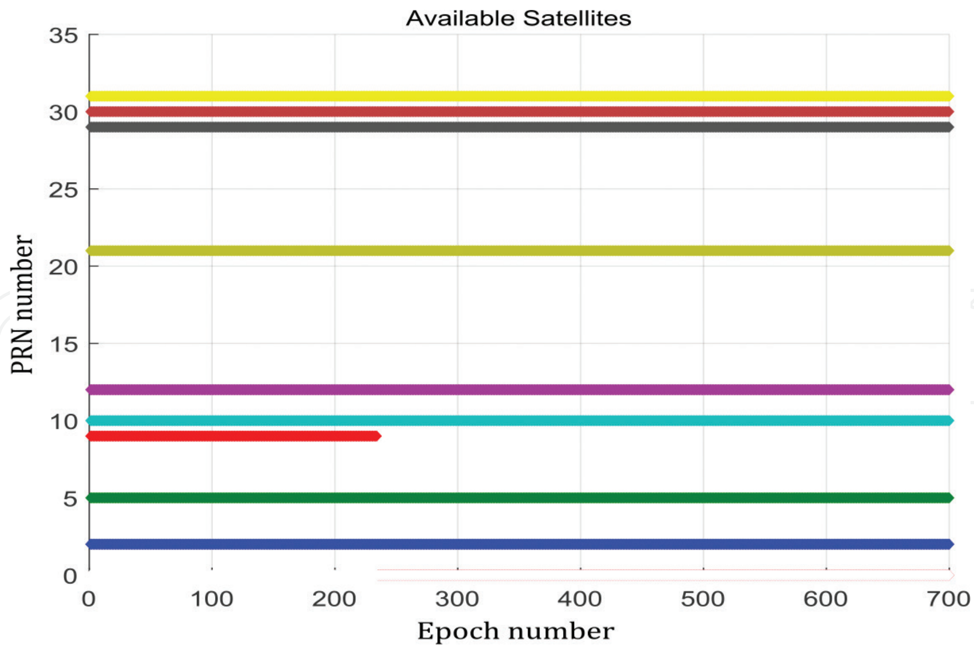

Figure 5. Satellite availability in a clean scenario.

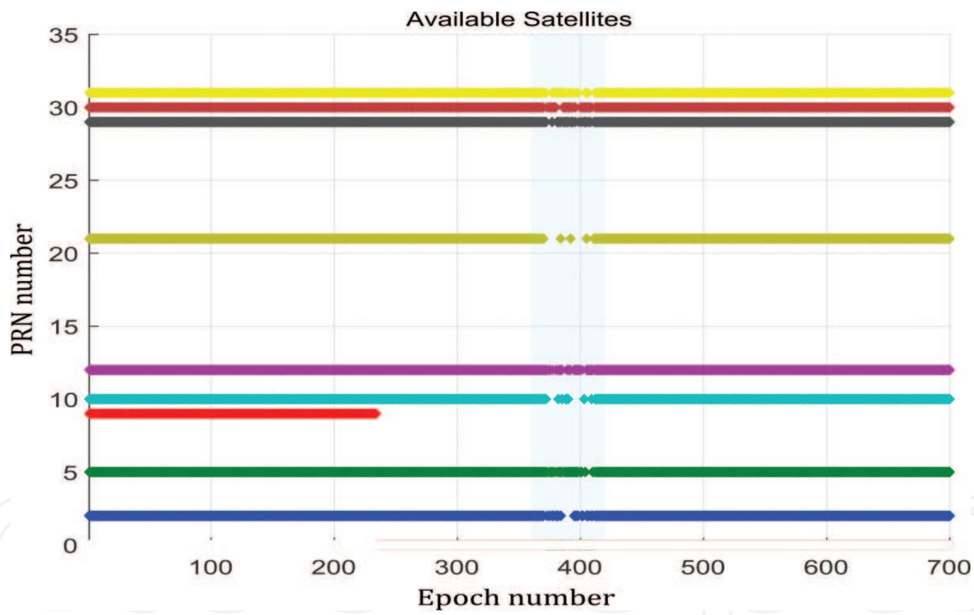

Figure 6. Discontinuity in satellite availability during the presence of a jamming signal.

(GBAS), which are approved by the US Federal Aviation System (FAA). These systems, though local, efficiently help in mitigating GPS signal outages. Moreover, they are robust against GPS signal jamming. Jamming-free navigation systems, e.g., Inertial Navigation Systems (INS), are an excellent alternative to rely on under jamming conditions.

2.4.3. Signal spoofing

GNSS signal spoofing is the creation of a faked GNSS signal that looks authentic to the GNSS receiver. Signal spoofing is more harmful than jamming because it is not readily detected.

The receiver can be fooled by the spoofing signal, which in turn affects its navigation solution. Furthermore, using correlation techniques to detect the spoofing is not feasible because the received signal is statistically correlated with the authentic GNSS signal, unlike the signal jamming case [30]. The effect of signal spoofing in degrading the navigation solution can have serious impacts in both military and civilian applications, especially those related to safety-of-life services.

Research is ongoing to find reliable techniques for mitigating the effects of spoofing attacks [31]. One example of such techniques is based on the signal direction of arrival (DOA). If the GNSS receiver and its antenna can detect the signal DOA, this can be used to reject the spoofing signal. This depends on the fact that, in most cases, the fake signal will be coming from a ground transmitter and therefore has a low elevation angle. On the other hand, the elevation angle of authentic signals can be predicted from the broadcast ephemeris [31].

2.5. User equivalent range error

After applying the appropriate models and the data in the navigation message to mitigate for the errors, one can use the so-called user equivalent range error (UERE) to quantify the total effect of the remaining errors on pseudorange measurements [2]. The metric, defined as the root sum square of the "unintentional" errors discussed above, is used to analyze the accuracy of the GNSS positioning solution under two assumptions. First, the measurement errors for all the satellites are uncorrelated; second, the independent errors are affecting the pseudorange measurement equivalently [4]. It is worth mentioning that the UERE is typically combined with the dilution of precision (DOP) to meaningfully express the expected accuracy of the GNSS positioning solution. The DOP measure is discussed in the next section.

2.6. Dilution of precision

One parameter that is independent of the cleanliness of measurements but plays a role in the accuracy of position accuracy is the DOP. This factor depends on the geometry of visible satellites; the better the geometry is, the lower the DOP, and, hence, the better the position solution. **Figure 7** visually depicts the concept of DOP. **Figure 7(a)** shows ideal case where signals from two satellites would form circles that intersect at the receiver position assuming the receiver has perfect measurements for the signal which is never true due to GNSS errors. **Figure 7(b)** represents a practical scenario in which uncertainty in measurement makes the virtual circuits radii a little ambiguous. The intersection region characterizes the area of possible receiver positions.

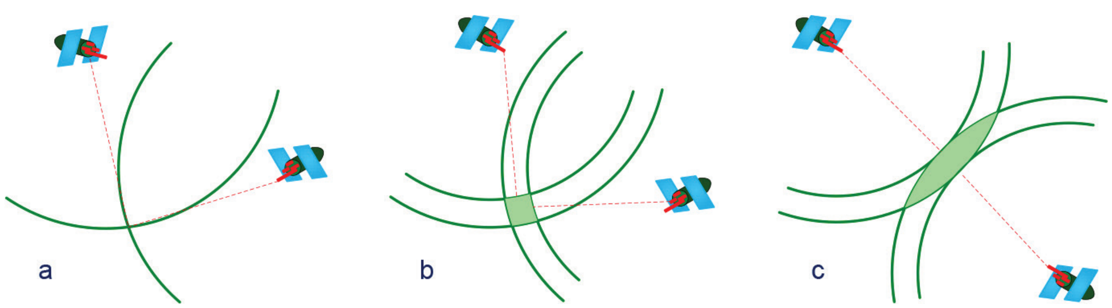

Figure 7. Dilution of precision with range measurements in 2D. Courtesy of Noureldin et al. [2].

This region could have a totally different shape as in **Figure 7(c)**. This solely depends on the geometry of seen satellites. DOP is used to select which satellites should be included in position calculations. An ideal receiver would select only the set of satellites with the minimum DOP [32]. The DOP number is unit-less, and calculating it requires knowing only the receiver and satellites' positions, i.e., no measurements are needed [4]. Hence, DOP could be computed before the journey to plan for trajectory data collection [2].

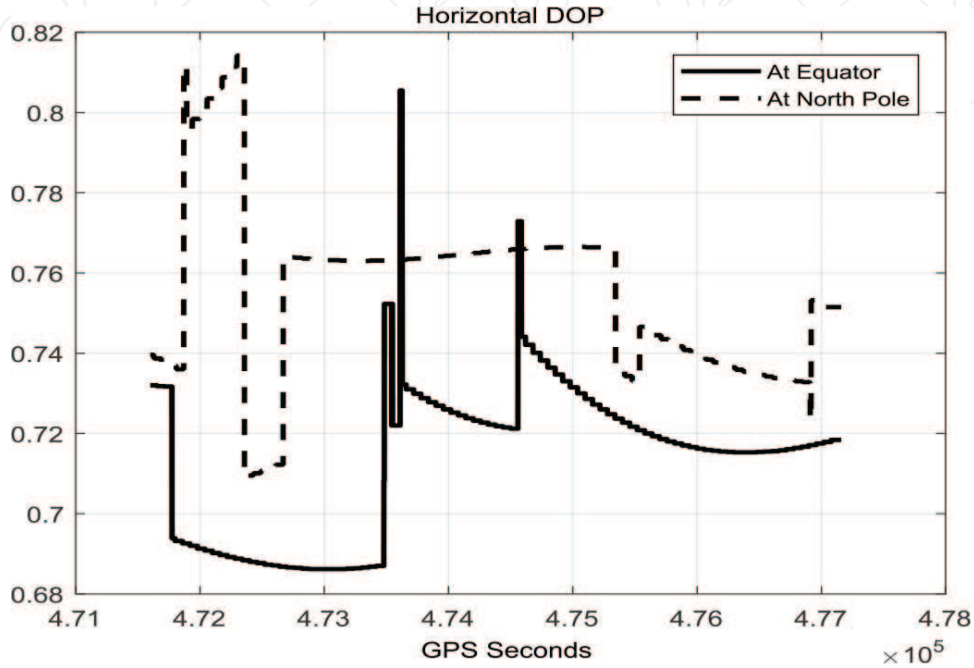

Figure 8. Horizontal DOP values at low versus high latitudes.

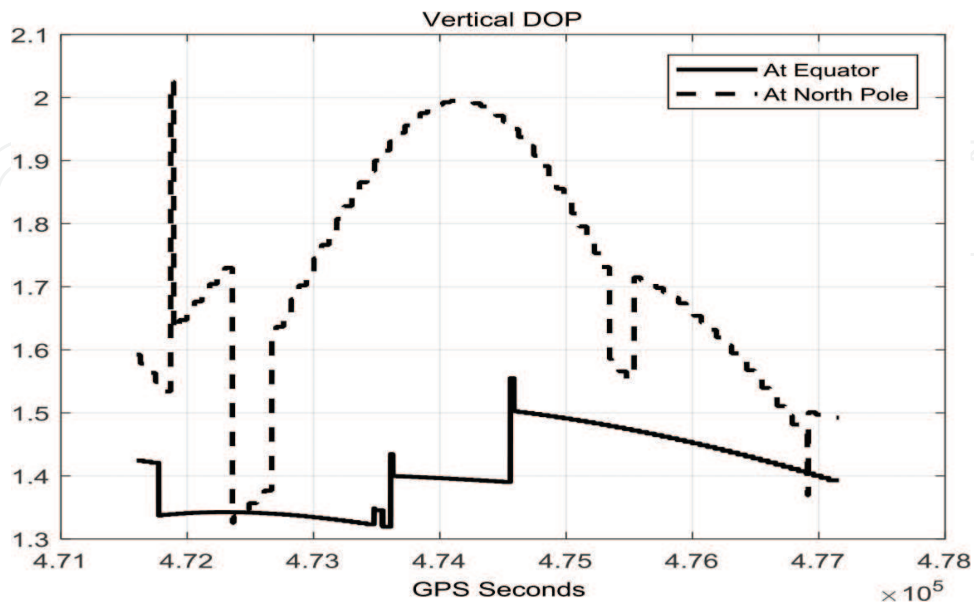

Figure 9. Vertical DOP values at low versus high latitudes.

DOP or the geometric DOP (GDOP) is the general term to describe the geometry of satellites; however, there are subcategories of this. Horizontal dilution of precision (HDOP), vertical dilution of precision (VDOP), and position dilution of precision (PDOP) are examples, to name a few. Simulation DOP values, using GPS only constellation, are shown in **Figures 8** and **9**, respectively, for low latitude (Equator) versus high latitude (North Pole) areas. It can be seen from both figures that DOP values at the Equator are always lower due to better satellite geometry. It can also be noted that GPS provides better HDOP against VDOP due to the arrangement of satellites and their orbits. The accuracy of the obtained/expected GPS solution is expressed as the product of the pseudorange error factor (i.e., UERE) and the geometry factor (i.e., DOP) [11]:

$$\textit{Error in GPS solution} = \textit{pseudorange error factor} \times \textit{geometry factor} = \textit{UERE} \times \textit{DOP} \tag{9}$$

As an example on this, a UERE value of 9 m and an HDOP value of 1.4 will indicate a horizontal position accuracy of 12.6 m at the two-sigma level.

3. Conclusion

GNSS signals have low power levels, and hence they are prone to many errors. These errors have various causes, scales, and, hence, consequences. This chapter discusses and classifies GNSS error sources according to their nature and effects. Errors related to the receiver and satellite clocks form one category—clock errors. Signal propagation errors explore a wide range of factors impacting the signal throughout its journey between the satellite and the receiver. Intentional error sources are grouped together. Whenever possible, diagrams and figures are used to explain the error type and/or size of the effect. Common error measure terms, including the user equivalent range error (UERE) and the dilution of precision (DOP), are also presented. Some of the GNSS errors could be as small as a fraction of a signal cycle, e.g., receiver noise error, whereas other errors can be in the order of dozens of meters, e.g., ionosphere and multipath. Receiver clock bias can grow up to thousands of meters and, thus, needs to be modeled. Intentional error sources can completely deny the GNSS services. Regardless their scale, GNSS errors need to be mitigated to achieve accepted navigation accuracy. In addition to exploring each error type, this chapter mentions the best ways to address them.

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