GNSS Limitations During Position Determination and Receiver Rerformance Testing Using Android Mobile Application

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Abstract **– Wide GNSS (Global Navigation Satellite System) availability has its advantages, however, in that case the system is exposed to a large number of external influences, from interference with other signals to deliberate blocking and jamming. There is also a huge increase in GNSS user number for both professional and private purposes. The technology of protection and regulation is partly behind the technological development and leaves room for undesired impacts from both natural and artificial causes. Through this paper GNSS errors are described using an android mobile application, "GNSS Analysis Tool", that allows observation of the GNSS signal characteristics.**

Keywords **– GNSS, performance, errors, signal testing, GNSS Analysis Tool.**

1. Introduction

Satellite systems for positioning and navigation such as GPS (Global Positioning System) and GLONASS (GLObal Navigation Satellite System) are covered in common name global navigation satellite system or GNSS. This system enables the determination of position all over the Earth, with exception of few specific places such as: places inside the buildings, inside tunnels, caves, garages, underground locations, and under water.

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GNSS is a satellite network that transmits continuous code information by which it is enabled precise determination of positions on the Earth. GNSS can secure continuous and accurate positioning in the case of the availability of four or more satellites. Of course, if the receiver accepts more signals, its place can be determined faster and more accurate [1]. The GNSS devices are used in various activities such as traffic, tourism, security, maritime, aviation, and geodesy.

Depending on the user need, every navigation system or system that is potentially applicable for navigational purposes, have to satisfy special requirements in terms of accuracy, integrity, continuity, availability, position determination start time, time of satellites initialization, endurance, interoperability, which are explained in more detail in chapter 2 of this paper. Chapter 3 provides an overview of GNSS system positioning errors, which includes: errors due satellite geometry, multipath, errors caused by solar activity and radio-frequency interference, satellite clock and receiver clock errors, relativistic effects, ephemeris errors /orbital errors, ionosphere and troposphere influence, jamming and deliberate signal interference. In Chapter 4, we introduced test results using Android mobile apps.

2. Key GNSS Performance Parameters

The quality of the positioning information is normally demonstrated by seven key parameters: accuracy, integrity, continuity, availability, time to first fix, robustness and authentication, which are defined as follows:

The system accuracy presents the superposition degree between the estimated and measured position with the real position at a given time. Its purpose is position determination in the tridimensional coordinate system, and the movement speed of user GPS receiver. Neither GPS nor GLONASS satellite navigation systems for civil users do not enable the insight into the state of satellite health, so the user does not know for eventual satellite damage and data errors [1]. System errors can appear in the control segment, satellite, and user segment.

System integration is an assurance that all system functions work inside the operative tolerance limits with the possibility of signal anomaly detection that could cause navigational errors bigger than normal. If the failure appears on the satellite's transponder, that satellite will not emit signals and it would not affect the positioning calculations. However, if satellite transmits signals, but there are some irregularities in transmission process that are the source of inaccurate data, could result as the positioning error is bigger than it is allowed . This error will be noticed by Earth control segment and it will deliver corrections to the satellite, in whose navigational message are contained data about the state of the satellite. That data can be emitted with big delay considering the conception of correct data transmission from the control station to satellites, what for example, in aviation could be fatal.

System continuity can be defined as the probability that the positioning service is supported through all time from the user's start-up of some operation till it ends without the interruption. Continuity is the likelihood that the specified system performance (accuracy and integrity) will be maintained during the operation phase, assuming that the system was available at the beginning of that operation phase [2].

System availability shows the percentage of time in which the positioning service is usable inside the defined time interval [3]. That means that GPS is projected where 95% of Earth's area will be in 95% of time covered with at least four different satellite navigation signals, which presents the necessary condition for determination of tridimensional user receiver's position.

Time to first fix is the measure of the time that GPS navigational device need for getting satellite signals and navigational data and calculating the first fix (first position). After the receiver accepts the satellite signal, it starts to get information about other satellites in that constellation, what is named almanah. Many receivers can use even twelve channels at the same time, what enables faster determination of the first fix [4].

System robustness represents the ability of systems or system elements to withstand levels of interference or / and stoppage without significant deterioration or loss of performance [5]. Complex terrain and environment will cause frequent interference with signal reception and signal processing.

System authentication (authentication) is the system ability to provide the user with trusted signals sources (eg specific GNSS constellation), thus protecting the user from cyber-attacks and intentional interference. The GNSS device automatically recognizes and rejects such signals.

Other parameters which do not directly relate to the GNSS performance are also important for GNSS-based technologies as power consumption, resilience, connectivity, interoperability and traceability.

3. Errors During Position Determination

The accuracy of determining the position or speed of a GPS user depends on various factors. Positioning errors (Table 1)[6] can occur due to geometric and systematic errors.

Table 1. Error values expressed in position deviation

Ionosphere	5 to 7 m
Ephemeris error (predictions)	2 to 3 m
Satellite clock	1 to 2 m
Multiple signal way (multipath)	1 to 2 depends on surrounding
Receiver's noise and resolution	0.3 to 1.5m
Troposphere	0.5 to 0.7m
Other errors	0.5m

The sources of GPS positioning errors are described in more detail below, as follows:

The influence of ionosphere and troposphere

On the path from satellite to user on Earth, the GPS signal passes 97.5% of the traveled path through the vacuum, which does not affect its propagation, and about 2.5% of the time passes through the layers of the ionosphere which causes a signal delay and thus errors in distance measuring [7]. This small percentage is enough to disrupt the signal and produce a positional error of several meters.

When larger variations in ionosphere electron density occur, the passing signal will delay or change its original path length [8]. The ionosphere works as a dispersing medium, which means that the delay of the ionosphere is frequency-dependent. Ionospheric delay presents one of the significant errors of positioning via GNSS. For two-frequency receivers, using the ionospheric correction models, this first order error can be eliminated, and with it 99.99% of the ionosphere delay [9]. On the other side, in single frequency receivers, the ionospheric delay should be modeled or estimated. The layer of the troposphere is lower and thicker than the layer of the ionosphere and it causes also signal delay. This is the delay equal at all frequencies, so it cannot be eliminated by a two-frequency receiver. The pseudorange measurement error due to the tropospheric delay is approximately the same for all satellites with an elevation greater than 10 °, so it can be easily corrected. Humidity causes variable delays. This influence is of local character and changes faster than ionospheric influences, making it more difficult to correct the error. Humidity in the troposphere affects the propagation of radio waves, regardless of their frequency, which can introduce an error of 0.1 to 1 meter. The changes in moisture are fast and this error is small but complex for correction.

Ephemeris errors /orbital errors

The receivers measure the position of satellites based on the information contained in a navigational message known as satellite ephemeris. The ephemeris parameters are estimated in the control segment after which they are sent to the satellites. The satellites broadcast updated ephemeris data every 2 hours [9]. Satellites motion parameters are forecasted based on ephemeris, obtained from optimally filtered trajectory measurements in the previous week, which leaves room for error relative to the actual orbit [2]. The ephemeris error for a particular satellite is identical to all GPS users worldwide [10]. The errors are in the order of 2 to 5 meters in size.

One way to increase the accuracy and availability of GNSS receiver solutions is to use all satellites 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 development stage to achieve global coverage, such as the European Galileo and China's BeiDou system. Each GNSS has its own time processing system, and therefore there are some inter-system mismatches that should be considered with multiple constellations. This can be achieved by computing the unknowns, which represent the time difference between the added GNSS constellation time and GPS time [9]. We can conclude that rules harmonization and technology standardization are very important for global coverage integrity.

Satellite clock and receiver clock errors

Each GPS satellite contains a precise atomic clock that controls the transmission time of a signal. Although the clocks are fairly accurate, the errors due to the clock oscillators can be large enough to require corrections. Corrections are also needed due to the fact that it is difficult to precisely synchronize the clocks of all satellites. Satellite clock errors appear due to the constant time movement of the satellite atomic clock relative to the system time in the ground stations. These deviations can reach up to 976 ms within 24 h. That is why, once a day from Earth, a satellite correction signal is sent, on the basis of which a model with correction coefficients is formed. These coefficients are broadcasted in the navigational message and they are used in the user's receiver [11]. Also, the error depends on the clock type, and it is turned out that cesium clocks show fewer errors in a long-time period than rubidium clocks. The measuring distance error because of receiver's noise presence derives from limitation of electronics inside the receiver. A good quality receiving device should minimize this noise. Usually, the receiver performs the test independently before starting [4]. The noise of the receiver is considered white noise; thus it is not possible to remove it completely. Errors like this include a wide spectrum of noises.

Multipath

The signal transmitted from the satellite reaches the user directly, along with the signals that bounce off objects (other planes, various objects such as buildings, canyon walls, solid ground, overlying surface, especially when flying above sea, etc.) and thus cause an error . Receivers also receive bounced signals (multipath multiple times). Reflections whose power can be compared to the direct signal could form on the receiver as the main signal. The delay and frequency of this signal does not correspond to the delay and frequency of the direct signal. Receivers with a help of filtering systems reduce or completely eliminate these reflected signals. For a large signal delay, the receiver itself recognizes the reflected signal and reject it automatically . A special antenna must be used to identify the signal with a shorter reflection delay. Rejected short delay signals are harder to filter because the effect is almost the same as that of standard atmospheric delay. The reflection errors are relatively small, ranging from 0.1 to 2.7 meters [11]. The errors described are very important to consider because a large number of receivers are just used in urban areas where this error is most relevant. This error affects a small number of GPS users, around 5%, and applies mostly to users in urban areas [12].

Relativistic effects

During the process of measuring the distance between satellite and receiver Einstein's theories of general and special relativity are taken into account. To reach a level of precision from 6 to 10 meters, atomic clocks on the satellites should have accuracy from 20 to 30 ns. However, considering satellites are permanently moving on the big altitudes in regards to an observer at Earth's surface, effects predicted by Special and general theory of relativity should be taken into account. At the height where the satellites are moving, the special theory of relativity predicts the slowdown of satellite clocks for approximately 7 μs per day, while the general theory of relativity predicts the acceleration of satellite clocks for approximately 45 μs. We can say that these phenomena contradict each other. The common effect of special and general relativity is 38 μs faster satellite clocks than the main reference clock on Earth [13]. If these "relativistic effects" were not taken into account, it would be very difficult to determine the position using a GPS device.

Errors caused by solar activity and radio- frequency interference

During solar eruptions, the Earth's magnetic field is disturbed by the entry of particles ejected by solar eruption in the area of the magnetosphere. The impact of this phenomenon on the operation of satellites is significant. At lower altitudes, satellites are constantly slowed down by friction. During solar eruptions, the density of the atmosphere can be increased to a level that causes a sudden loss of height of the satellite and its combustion in the atmosphere. Satellites in higher orbits can also be damaged from smaller-scale solar activities. During geomagnetic storms, satellites can lose their link temporarily or permanently [11]. In addition to solar interference, the satellite signal is prone to interference with other waves in different radio frequency spectra.

Errors due satellite geometry

It refers to the relative position of the satellite at some point. The ideal geometry of satellites exists when the satellites are positioned at a great angle relative to one another. Adverse geometry occurs when satellites are positioned in a straight line or are closely grouped [13]. On the large geographical latitude, geometry and the number of visible satellites is slightly worse what also can affect the increment of this error [12]. That is why is important to have a global coverage no matter which constellation we are using.

Jamming and deliberate signal interference

The use of a global positioning system in navigation, tracking, modern, smart and communication networks has shown that there are increased incident rate of cyber-attacks on GPS receivers, despite the continuous development of technologies [14]. For example, today it is possible to change the ship direction or direction of unmanned aircraft by simply GNSS signal interference, jamming or spoofing.

Global Positioning System jammers generate and transmit radio frequencies similar to real frequencies with amplified noise [15]. This cause loss of satellite signals, difficult signal interpretation, or the inability for continuous monitoring.

Jamming with the characteristics of unpredictable, deliberate, human-induced, untreated or sophisticated, local or widespread GPS disturbance represent the emission of radio frequency energy with sufficient power and with the appropriate characteristics to prevent receivers in the target area to track GPS signals. Jamming involves the use of radio transmitters / transmitters that emit a signal through one or more GPS / GNSS frequencies in order to increase the noise level or overload the receiver circuit. This results in the GPS / GNSS receiver are unable to receive weaker satellite signals because it receives stronger signals transmitted by the same frequency from another device, which overlaps the required signal from the satellite with its intensity. Interference as a term closely related to the term jamming and is an unintentionally produced radio frequency waveform that raises the noise level of receiver processing. Jamming is a deliberately induced interference with intent to degrade or deny the operation of the target receiver. Spoofing is caused by radio frequency waves that aim to mimic real signals in a certain way. These signals degrade, disrupt, or interfere with the receiver's operation when processed, resulting in the replacement of an actual signal with a manipulated one, whereby the user does not realize that he is using the wrong GPS signal and continues to rely on the same.

Spoofing is caused by radiofrequency wave shapes which have a goal to imitate real signals. These signals degrade, disturb or bluff the work of the receiver when they are in process, and it results in replacement possession of real signal with manipulate, where the user does not understand that he uses the wrong GPS signal, and continues with the reliance on the same one.

Spoofing is described as an unpredictable, deliberate, human-induced, sophisticated, local, and demanding technique that requires knowing the exact satellites from which a particular receiver receives a signal, which generally assumes that the interfering device is moving and is in a close distance to the receiver.

According to [12] a risk model and complexity assessment of an individual error was developed, where each error was assigned a certain number of points according to each criterion (sensitivity, consequences and threats, majors and possibility of execution). This paper concludes that deliberate interference and blocking by humans are the most complex to predict and correct.

4. Accuracy and Availability of Satellite Position Determination Service Testing

Practical testing was performed with an android application "GNSS Analysis Tool". The application allows us to measure a range of performance indicators that directly affects the level of GNSS safety criteria described in the paper. Testing was conducted within a University campus in Sarajevo. The terrain is very complex, composed of buildings and trees as well as parts where there are no obstacles. The pseudorange generation method used by the android chipset is the common reception time method where all pseudoranges in an epoch and in subsequent epochs are calculated relative to the very first satellite signal to arrive at the first epoch of observation. [16] A GNSS receiver process signals and provides the user with an estimated PVT solution. A generic block diagram of a GNSS receiver is shown in Figure 1 [17].

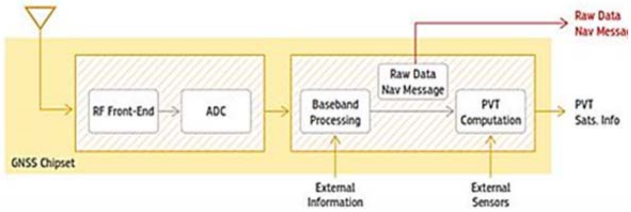

Figure 1. Generic block diagram of a GNSS receiver

The RF block (the left side of the diagram) includes the antenna and front-end, which are required for analogue signal processing. It can also include a low noise amplifier, filters and an intermediate- frequency down conversion. The final element in the block is the Analogue-to-Digital Converter (ADC). Additional data can be used to improve precision such as external sensors in a smartphone, the base- band and PVT processing blocks (right side of the diagram) are software-based signal processing units that are designed to operate on a general-purpose hardware. The baseband processing is responsible for acquiring and tracking of the GNSS signals and decoding the navigation messages. Assisted data (external information) can be provided to reduce the time to fix [17].

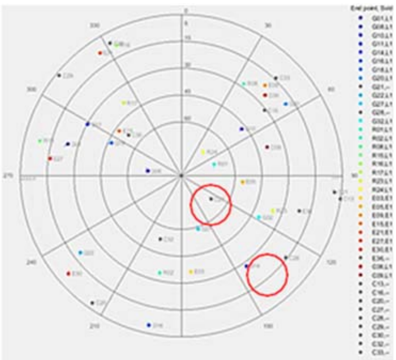

Figure 2. Satellite position on the horizont relative to the receiver (G27-near the center and G37)

In this testing we used a google application for processing and analyzing GNSS raw information. This tool allows us to take measurements and view measurement data and receiver performance in the mobile phone. Three navigation systems were used during measurements; GPS, GLONASS and Galileo, which were mostly available systems in the testing area. Two Android mobile phones were used in the measurements: Xiaomi Redmi Note 7 and Samsung Galaxy A50. The terrain in the testing area was complex, primarily in terms of obstacle presence. The aim was to examine individual receiver errors in different terrain conditions. In this testing, we tried to simulate the effect of signal reflection between multiple buildings and its effect on the GNSS receivers accuracy. The receiver was also moving in different compass directions, which also had influence in the quality of signal reception as you can see in Figure 2.

In this application you can select any subset of visible satellites. The basic task is to read the calculated pseudorange errors, including the mean and standard deviation. One of the first things that can be noticed is that there is no direct pseudorange observation, instead the pseudorange is derived from satellite time reception information. In the figure 3 we can notice that the signal power of the individual satellites is very poor even though they are 10 degrees above the horizon. A signal whose noise-to-signal ratio S / N which is less than 25 dB-Hz is considered too high and cannot be processed. There are also differences in the quality of signal processing depending on the constellation of the satellite. In our measurement, the Xiaomi receiver did not meet the basic signal strength criteria. One of the important factors during measurement is the position of the antenna on the mobile phone itself.

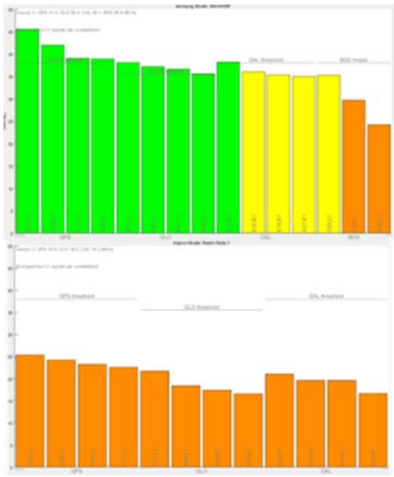

Figure 3. Signal strength comparison between two receivers (Samsung A50 / upper, Xiaomi Redmi Note 7 / lower)

SNR (Signal to noise ratio) is usually expressed in decibels. It is the ratio of signal strength to noise power for a given bandwidth. S / N0, on the other hand, it is usually expressed in decibel-Hertz (dB-Hz) and refers to the ratio of the carrier signal power to the noise power for a given bandwidth. The white noise source in the receiver is described as the antenna noise temperature. One of the criteria of the receiving system is its ability to receive very weak signals: its sensitivity.

For a given bandwidth, the sensitivity is determined by only two factors: antenna amplification and the equivalent noise temperature of the receiving system. The noise temperature of the receiving system consists of the noise temperature of the antenna (Ta), the attenuation of the cable converted to noise temperature and its own internal noise of the receiver or preamplifier (Trx).

These parameters determine the signal-to-noise ratio (S / N) that a linear receiving system has at its output [18]. In the Table 2 below, we present the measured parameters of both receivers. We notice a significant difference in achieved reception performance.

Table 2. Receiver parameters

Satellite constellation	Mean of strongest 4 mean (C/No)		Referent treshold (dBHz)		Nuber of visible satellites	
	A50	Xi7	A50	Xi7	A50	Xi7
GPS	41.4	23.9	38.0	38.0	11	11
GLO	36.9	18.5	35.5	35.5	8	7
GAL	36.1	19.3	38.0	38.0	7	7
BDS	29.8	-	38.0	-	3	-

On the Figure 4, we notice power-varying signals, and increased receiver filtering for better reception which ultimately caused significant signal oscillation. We compared 2 satellites that were located east of our location. At one point they were invisible to the receiver due to nearby building obscuration.

The measurement of distance in the following case will involve the sum of the errors of the ionosphere, troposphere and orbit. As we can notice satellites that are high on the horizon, and they have a smaller position indicating error.

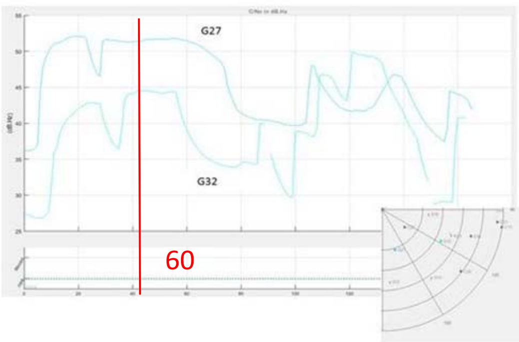

Figure 4. The signal strength of 2 GPS satellites G27 and G32.

Due to the receiver position, we can see that the satellite G27 gives a better signal because it is located at a larger horizon angle . At 60 seconds, we notice a significant attenuation of the signal due to a satellite which is located east from the receiver and is obscured by the building next to the receiver.

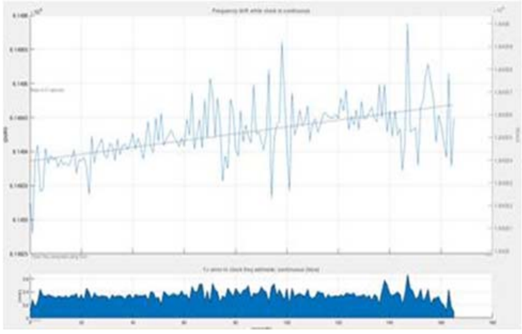

Figure 5. Recieve clock deviation

Figure 5 shows the clock deviation in the receiver that continuously monitors the satellites. The receiver in this particular case had no interruptions while monitoring the satellite. The receiver consists of a temperature compensated oscillator (TCXO). Quartz crystals are naturally extremely stable in terms of their natural oscillating frequency, yet exhibit a deviation from crystal to crystal. This deviation is typically measured in parts per million (ppm) or parts per billion (ppb). Frequency stability means the variation of the oscillator output frequency due to some external conditions such as temperature variations, voltage changes, etc. Usually stability is expressed in ppm or ppb, which is most commonly expressed in Hz. So if we have a 1 ppm error, it means 1/10 * 6 partsof the rated frequency. The quartz oscillator has an output frequency of 1 MHz (1000000 Hz) and has a frequency stability of 5 ppm, which means that the frequency will vary in 5 Hz. Tolerance stability can in some cases be expressed as a deviation from the nominal frequency eg 0.01% = 100ppm.

The good behavior of this oscillator can be defined if the frequency deviation is within + -500 ppb and the total deviation is within + -2 ppb / s. The deviation on the Samsung A50 receiver was 0.01 ppb / s and the Xiaomi's 0.03 ppb / s.

Figure 6. Comparison of the receiver position calculation (A50 on upper image, Xiaomi on lower image, with (green) and without Kalman filter(red))

Figure 6 shows the measured paths from two different receivers on two different mobile phones. On the lower image is the Xiaomi Redmi Note 7, and based on the analysis we performed earlier, we can notice much larger horizontal deviations compare to the top image.

The position approximation was performed using a Kalman filter, which is a recursive algorithm designed to calculate corrections in a system based on external measurements. For better position determination , [19] propose a sensor fusion of WiFi, pedestrian dead reckoning and landmarks by using a Kalman filter algorithm.

5. Conclusion

The GNSS signal has very low power, and is therefore exposed to many internal and external factors. This paper aims to classify and identify the most significant errors and limitations. GNSS technology is developing intensively, however, the number of users also is growing exponentially. The number of GNSS satellite systems is growing rapidly (GLONASS, GALILEO, BEI DU, etc.) and with it new challenges are emerging. Main goal is to provide accurate, functional and continuous cover and navigation services to a large number of users around the world.The measurements shown in this paper describe and visualize large number of signal parameters. By simply using the GNSS andorid mobile application, we can investigate receiver performance in dynamic environments, especially in urban areas where signal interference is very high. We noticed a big difference in the signal reception on 2 different mobile phone receivers. This application gave researchers access to explore a large number of signal parameters. Future research should focus on signal testing in various indoors and outdoors environments.

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