DOP and Pseudorange Error Estimation in Urban Environments for Mobile Android GNSS Applications

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Abstract: Just a couple of years ago, GNSS (Global Navigation Satellite Systems) were available only for a narrow group of users. Currently, with the outbreak of mobile devices, they are accessible to anyone and everywhere. Urban navigation or searching for POIs (Points of Interest) had become an everyday activity. With the availability of consumer electronics and wireless technologies, each user can obtain information considering his or her location even in an unknown environment. Additionally, network operators and service providers utilize this location-based information for monitoring and maintenance purposes. This paper is focused on a study, considering the DOP (Dilution of Precision) and pseudorange error estimation in case of Android-powered smartphones operating outdoors. It describes a measurement campaign, carried out in varying urban environments, with two types of excursions (by car and bicycle), including two popular consumer devices from different manufacturers. Based on this, respective conclusions and remarks are given. This work aims to aid not only users, but also application developers as well as device manufacturers and retailers, when it comes to providing precise and reliable products and services.

1 INTRODUCTION

Nowadays, there is a wide group of GNSS (Global Navigation Satellite Systems) operating around the world. They utilize artificial satellites, constantly generating signals and transmitting them to the surface of the Earth. Mobile devices, particularly smartphones with a complex set of wireless modules, enable to take advantage of a number of available national and international systems, including: GPS (USA), GLONASS (Russia), Galileo (Europe/EU), BeiDou (China), NAVIC (India), and QZSS (Japan) (Quan, Lau, Roberts and Meng, 2016; Teunissen and Montenbruck, 2017). A brief description of GNSS, including utilized frequency band, is described in Table 1.

It seems that the variety of GNSS-based applications is unlimited. Currently, they are utilized in e.g. forwarding and logistics, aerial, road and sea transport, personal motorized and pedestrian navigation, searching for POI (Point of Interest), etc. Particularly, users rely on them in urban environments, especially at unknown locations. It is worth mentioning that currently every mobile device has an integrated circuit, responsible for processing GNSS signals (Gilski and Stefański, 2015; Chruszczyk, 2017).

Due to the popularity and widespread of portable devices, it seemed interesting to investigate the precision that modern smartphones can offer. Particularly, what is the accuracy of satellite positioning and navigation systems for urban mobility applications. That is why this study, concerning Android-powered terminals, was carried out.

2 MOBILE CONSUMER DEVICES

Due to the technological development, mobile terminals have evolved into functionally-sophisticated devices, such as smartphones.

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The Android platform is currently the most popular operating system worldwide.

Table 1: Modern GNSS satellite systems.

No.	Name	Frequency band
1	GPS	1.563–1.587 GHz (L1) 1.215–1.2396 GHz (L2) 1.164–1.189 GHz (L5)
2	GLONASS	1.593–1.610 GHz (G1) 1.237–1.254 GHz (G2) 1.189–1.214 GHz (G3)
3	Galileo	1.559–1.592 GHz (E1) 1.164–1.215 GHz (E5a/b) 1.260–1.300 GHz (E6)
4	BeiDou	1.561098 GHz (B1) 1.589742 GHz (B1-2) 1.20714 GHz (B2) 1.26852 GHz (B3)
5	NAVIC	1.17645 GHz(L5) 2.492028 GHz (S)
6	QZSS	1.57542 GHz (L1-C/A) 1.57542 GHz (L1C) 1.2276 GHz (L2C) 1.17645 GHz (L5) 1.57542 GHz (L1-SAIF) 1.27875 GHz (LEX)

As handheld devices become more popular, the role of an operating system grows significantly. Current Android-powered devices are full of integrated hardware, including IMUs (Inertial Measurement Units) such as cameras, gyroscopes, accelerometers, as well as various wireless interfaces, containing a build-in cellular and GNSS receiver. This OS enables third-party applications to make use of these hardware features and provides a suitable user environment (Gilski and Stefański, 2016).

2.1 Programming Android Terminals

As learning mobile programming becomes an increasingly sought after and valued skill, primary, secondary, as well as higher education institutions aim at designing and developing courses, books and related supplementary learning resources (Hendikawati, Zahid and Arifudin, 2019a), along with modern ICT (Information and Communication Technologies) tools (Hendikawati, Zahid and Arifudin, 2019b).

In (Prabowo, Rahmawati and Anggoro, 2019) authors developed an Android-based application for teaching junior high-school mathematics, integrated with a popular social-media platform, namely WhatsApp. Whereas, in (Hendikawati, Arifudin and Zahid, 2018) authors developed a computer-assisted application for statistical data analysis, also related to education and learning purposes.

In (de Oliveira, de Oliveira, Ramalho and Viana, 2016) authors assessed the performance of mobile messaging, under various research scenarios, including different distributions of the Android OS, mobile devices, as well as wireless network access technologies.

Android itself, as an open environment, is a member of the Linux family. The difference between the Android and Linux kernel, runtime environment, security and privacy risks, etc., is discussed in (Khan and Shahzad, 2015). Whereas, the matter of mobile security is further analyzed in (Ul Abideen, Ali Tariq, Shah Talha Naqash and Qaseem, 2018).

As shown, the Android operating system, and related consumer devices, are utilized for a number of purposes, even in testing and monitoring electrical components of machines. The matter of such an IoT (Internet of Things) system, as an element of the Industry 4.0 concept, is described in (Sharmilah et al., 2019).

2.2 Positioning Accuracy

The positioning accuracy of a GNSS system may be evaluated in a number of ways. The most popular one is based on CNR (Carried-to-Noise-Ratio), usually expressed in dBHz (Cisco, 2012). Another approach is related to the number of observed and monitored satellites, including the DOP (Dilution of Precision) coefficient, related to the geometry of the constellation, and its impact on precision (Langley, 1999). The DOP can be defined in a number of variants:

- GDOP (Geometric DOP) – related to the positioning accuracy in 4 dimensions (space and time).
- HDOP (Horizontal DOP) – related to the positioning accuracy in the horizontal plane.
- VDOP (Vertical DOP) – related to the positioning accuracy in the vertical plane (height).
- TDOP (Time DOP) – related to the accuracy of time measurements.
- PDOP (Position DOP) – related to positioning accuracy in 3 spatial dimensions.

Generally speaking, the lower the value, the higher the reliability (confidence) of positioning calculations. However, when DOP is close to or equal to zero, obtaining a position is not possible, due to too low signal level or severe interference. Whereas, when it reaches a threshold of 20 and above, the signal quality does not provide reliable measures as well.

Before 2016, Android-powered devices, up to Android Marshmallow 6.0, had limited access to navigation and/or positioning data. At that time, the API (Application Programming Interface) enabled to access basic information concerning the satellite's azimuth, elevation, SNR (Signal-to-Noise Radio), PVT (Position, Velocity and Time), status of the chipset (active or inactive), latitude and longitude data, estimated positioning accuracy (in meters), as well as NMEA (National Marine Electronics Association) data. This enabled a positioning accuracy of a couple of meters (most often 2-3 m).

Since 2017, the newly introduced version of Android, called Nougat (7.0), enabled to utilize raw positioning data (GSA, 2017). From then developers were able to use a set of dedicated additional classes and related methods in order to design more precise software, including information about the GNSS clock (for pseudorange error calculation purposes), how to decode incoming bits from available satellite constellations, as well as the time, code and phase of a particular carrier from a given satellite, not to mention the Doppler shift.

Further improvements included integrating the PPP (Precise Point Positioning) technique (Laurichesse, Rouch, Marmet and Pascaud, 2017), as well as sensor fusion, together with the mobile device's build-in light and pressure sensor, IMU (Inertial Measurement Unit), accelerometer, gyroscope, magnetometer, etc. Recent studies related to the subject of mobile positioning are available in (Specht, Szot, Dąbrowski and Specht, 2020; Su, Jin and Jiao, 2020; Guo et al., 2020; An, Meng and Jiang, 2020).

3 ABOUT THE STUDY

The study was carried out using two mobile devices, particularly smartphones. They came from different manufacturers, and are further labeled as Smartphone 1 and Smartphone 2.

The first one had a 8-core CPU (2.2 GHz), 3 GB of RAM, a 3000 mAh battery, and was powered by Android Pie (9.0). The integrated GNSS module was compatible with GPS, GLONASS, Galileo, BeiDou, and QZSS.

The second device had also a 8-core CPU (2.3 GHz), 4 GB of RAM, 4000 mAh battery, and was powered by Android Pie (9.0) as well. The integrated GNSS module was compatible with GPS, GLONASS, Galileo, and BeiDou.

All obtained data were recorded in the raw format, and then processed using the GNSS Measurement Tool as well as Matlab software. During both measurement and processing, we utilized our custom software, in order to obtain as much data as possible. The measurement campaign included 2 types of routes (square-shaped and straight line), 2 types of communication means (bicycle – low speed, car – high speed), and of course 2 smartphones.

4 RESULTS

In the first scenario, the route resembled a square, as shown in Figure 1. Whereas in the second one, the route resembled a straight line, as shown in Figure 2. Both routes were evaluated with a bicycle at an average speed of 8 km/h, and a car at average speed of 35 km/h. This route went along 3 streets (Twarda, Chwaszczyńska, and Okrąg) in the city of Gdańsk. It varied in type of structure and its closest neighborhood. Some part of it was surrounded by buildings, and some of it was next to an open terrain.

Figure 1: Layout of the square-shaped route.

Figure 2: Layout of the straight line route.

To start with, obtained results will be described taking into consideration the type of route (square-shaped and straight line), type of mobility (bicycle and car), and utilized smartphone (Smartphone 1 and Smartphone 2). Next, obtained results will be compared and discussed.

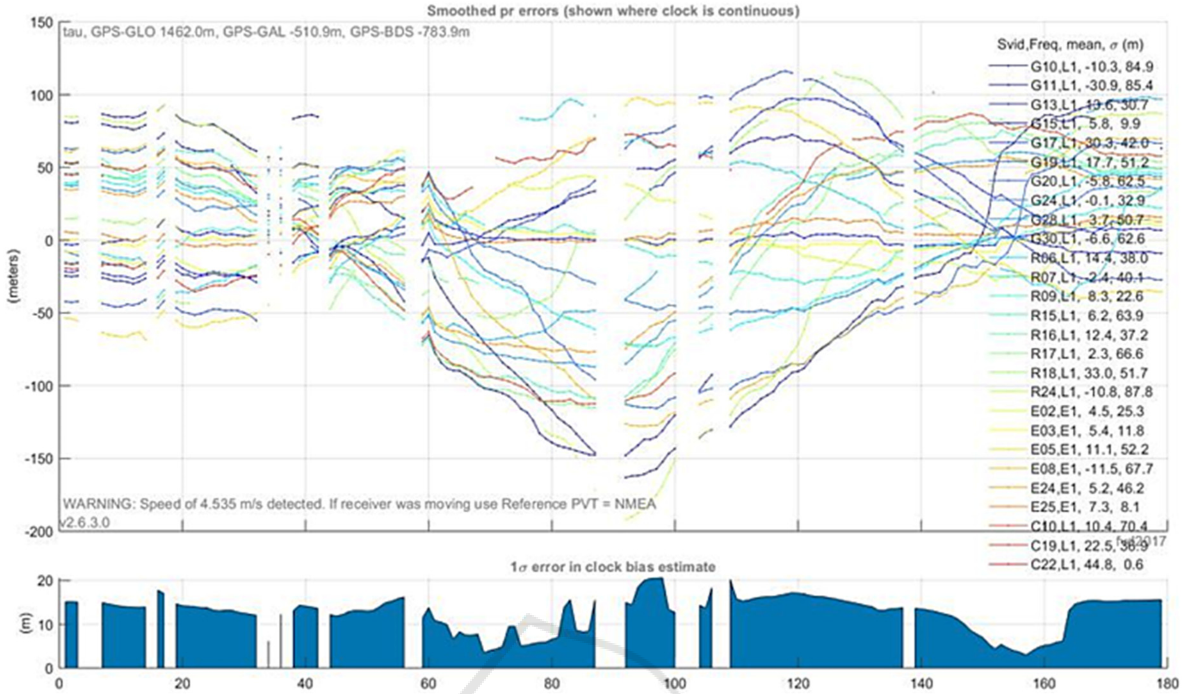

Figure 3: Pseudorange error – bike excursion along the square-shaped route with Smartphone 1.

4.1 Square-shaped Route: Bicycle Excursion with Smartphone 1

The HDOP value, for the GPS constellation, was close to approx. 1 in case of 7-10 observed satellites. When the number of satellites decreased, the HDOP value rose to approx. 2. In case of the GLONASS system the number of observed satellites dynamically changed between 5-8 satellites, whereas HDOP ranged between 0.8-1.56. The clock drift did fluctuate, with a maximum value of approx. 0.03 ppb/s.

The signal with the strongest CNR was observed for satellite C27 from the BeiDou constellation. This satellite, like C28 and C22, was observed only in the first few seconds of measurement. The signal strength from other BeiDou satellites was equal to approx. 20-25 dBHz. However, those signals had a big pseudorange error (from -6 to 4 m), and were not correlated to the estimated frequency clock. The signal strength itself was unstable.

The pseudorange error did exceed 50 m, especially at the crossroad of Twarda and Chwaszczyńska streets. To sum up, 95% of the pseudarange error was less than 59.6 m. The WLS (Weighted Least Squares) error was equal to 15.1 m (see Figure 3). This route runs between buildings only in some part. That is why the impact of multipath propagation was not significant. Furthermore, the terrain topology also had an impact on obtained accuracy, as the height difference ranged between 0-4 m above sea level.

4.2 Square-shaped Route: Bicycle Excursion with Smartphone 2

The absolute value of the clock drift was equal to 0.01 ppb/s. Most of the observed satellites had good geometry. In case of GPS the HDOP value oscillated around 0.9-1.2, whereas for GLONASS it reached 1-2.25.

The horizontal and vertical error, calculated based on WLS, oscillated around 0.0-0.7 m. However, this was not close to real values. According to obtained results, the amplitude of height reached 100 m, which is a huge error, as the real value was equal to approx. 4 m along the whole route

Obtained pseudorange errors were unconcise. They changed from positive to negative (see Figure 4). This clearly showed that positioning accuracy was low. Higher Doppler shifts were observed for GLONASS. It should be pointed out that BeiDou and Galileo satellites were not monitored during most of the time. Biases in the clock itself had a significant impact as well.

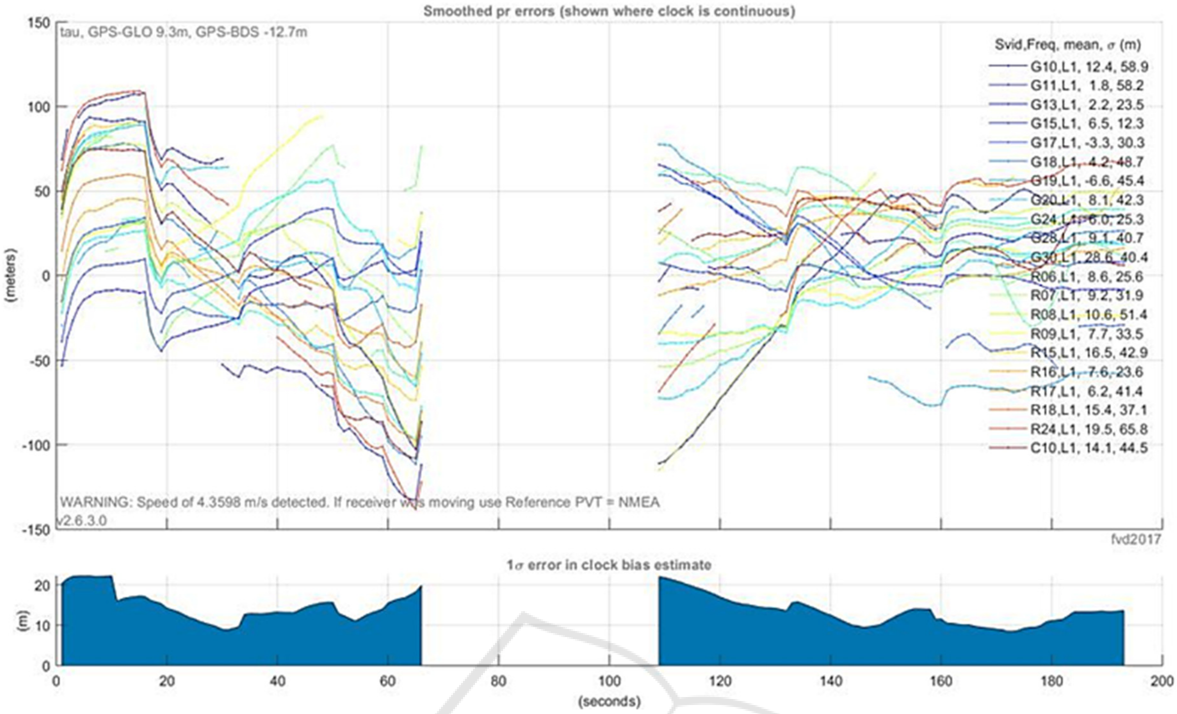

Figure 4: Pseudorange error – bike excursion along the square-shaped route with Smartphone 2.

4.3 Square-shaped Route: Car Excursion with Smartphone 1

The HDOP value for GPS was equal to approx. 1, and reached 2 when the number of satellites shrank to 4. In case of GLONASS, this parameter oscillated from 1 to even 5. During approx. half of the time, the clock was not concise, resulting in a discontinuous time of satellite observation, especially in case of BeiDou and Galileo. Not surprising, the strongest signal was observed when driving in open terrain (the number of observed satellites was also higher). During the measurement campaign, the clock was not stable. Moreover, a frequency drift was observed, equal to 0.18 ppb/s, with a stable clock bias.

The pseudorange error for GPS and GLONASS oscillated from -50 to 50 m (see Figure 5). When driving in open space, additional Galileo and BeiDou signals were observed. The highest pseudorange error was observed when the car was in the so-called urban canyon.

The WLS estimation was quite precise, especially in the second part of the drive test. At first even deviations of few meters were observed. During the first 52 s the vertical position was calculated with huge error (exceeding 5 m). Whereas, for the next 40 s, the accuracy was noticeably higher. However, at the end it reached 50 m. When utilizing WLS on raw data, we obtained more accurate results. The average vertical position was approx. at 0 m, whereas 50% of obtained samples resulted in 6.3 m and less.

4.4 Square-shaped Route: Car Excursion with Smartphone 2

In case of GPS the HDOP value oscillated around approx. 0.9-1.5, whereas in case of GLONASS it did not exceed 1.6. The clock was continuous, with a drift of -0.06 ppb/s. The clock shift was getting higher in a linear scale.

The pseudorange error, for most cases (95%) did not exceed 28.7 m. When the car drove among buildings, this error reached to approx. 100 m (see Figure 6). The highest Doppler shifts were also observed for G07 and G08 (30-50 s and 90-100 s), where the observed multipath effect was the strongest.

Results obtained using WLS were quite good. The horizontal error was less than 9.7 m for 50% of obtained samples, and less than 20.8 m for 95% of samples. The vertical error was less than 23.4 m for 50% of samples, and less than 44.6 m for 95% of samples.

Figure 5: Pseudorange error – car excursion along the square-shaped route with Smartphone 1.

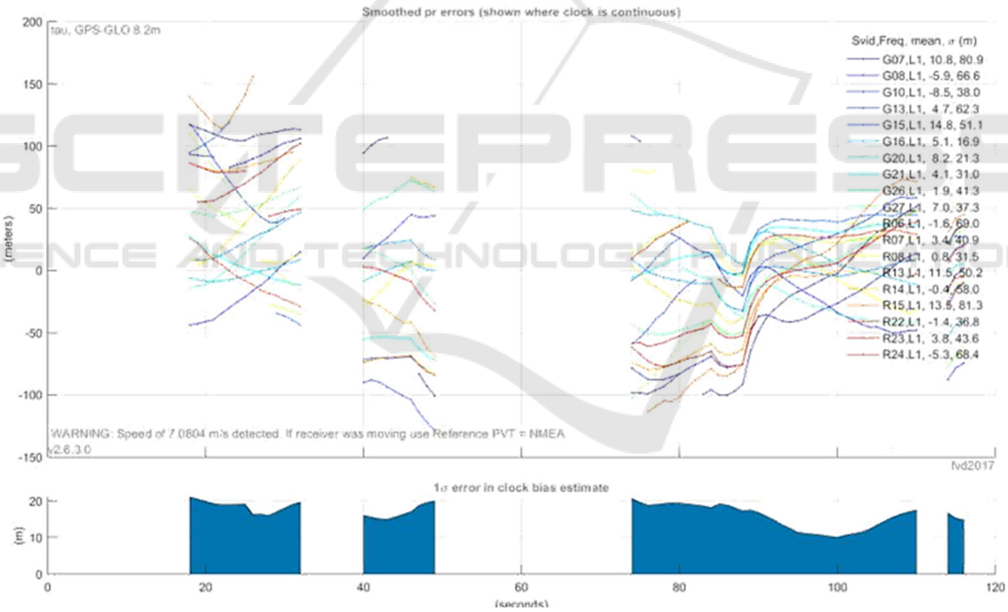

Figure 6: Pseudorange error – car excursion along the square-shaped route with Smartphone 2.

4.5 Straight Line Route – Bicycle Excursion with Smartphone 1

The HDOP value in case of GLONASS oscillated from 1.2 to 3. The signals from other satellite systems were stable. In some part of the measurement time, reception of Galileo and BeiDou was not possible, due to signal loss.

At first, the frequency drift rose with 0.45 ppb/s, then shrank with 0.15 ppb/s. Between 80-140 s, the receiver did not monitor satellites in a continuous way. That is why during this time the clock drift was not calculated. In other parts of the measurement time, the drift changed with -0.24 ppb/s (when moving from building surroundings to open space). The clock drift, calculated between 86-110 s, was equal to 593 ppm.

The biggest observed pseudorange error was equal to 150 m (see Figure 7). When surrounded by high buildings, we were not able to determine the

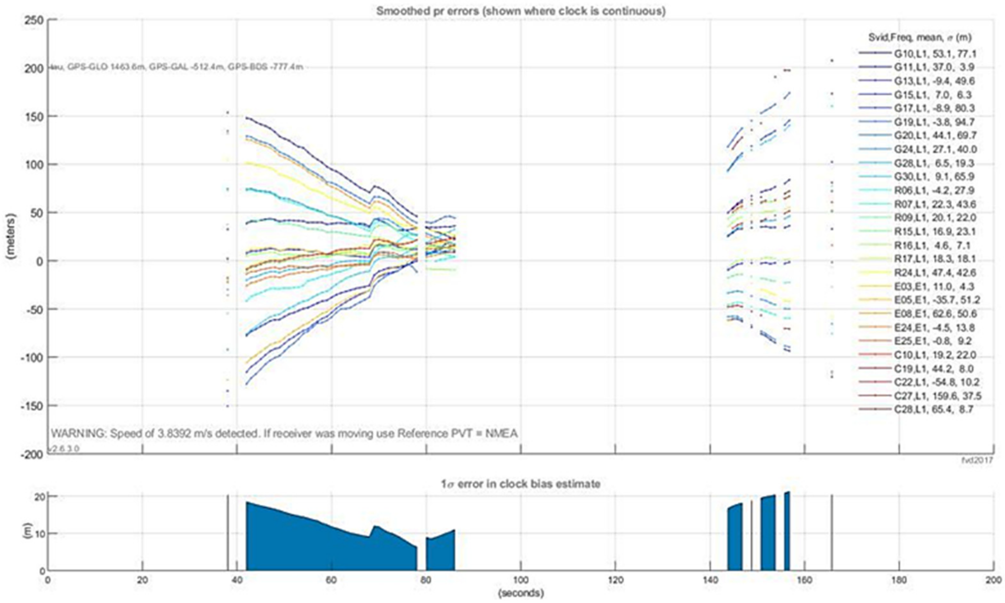

Figure 7: Pseudorange error – bike excursion along the straight line route with Smartphone 1.

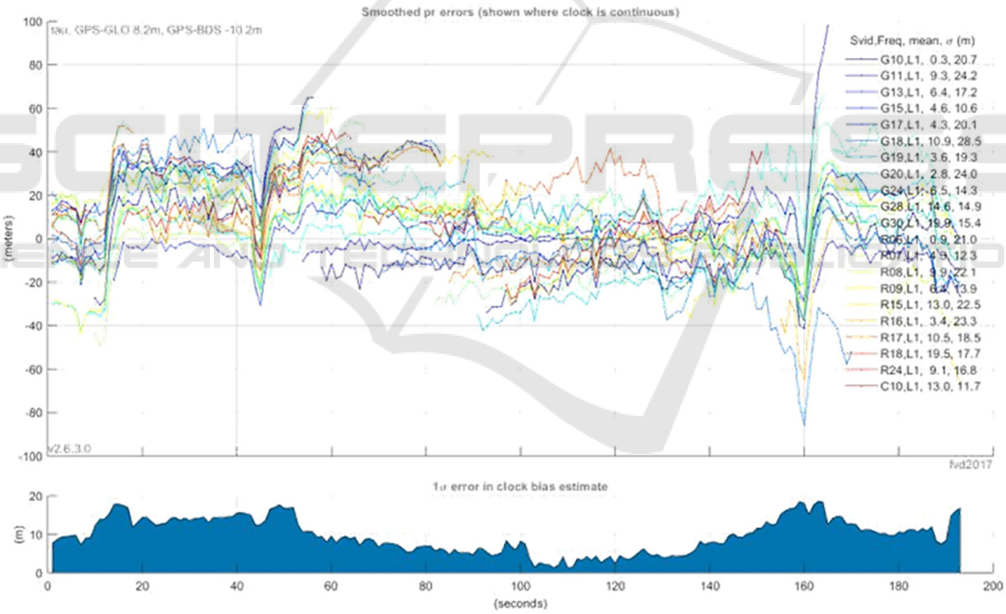

Figure 8: Pseudorange error – bike excursion along the straight line route with Smartphone 2.

error. A linear decrease in error may be observed, when the device reached open space. Position calculations using WLS provided an accurate estimation. Between 80-140 s, clock biases were encountered. The horizontal error for 50% of results was less than 164.5 m, and less than 235.1 m for 95% of data. In case of vertical error, it was equal to less than 28.4 m for 50% of data, and less than 215 m for 95% of data.

4.6 Straight Line Route – Bicycle Excursion with Smartphone 2

In case of the HDOP values for GPS, they oscillated around approx. 1.2, whereas GLONASS received approx. 2. This mobile device enabled stable reception for GPS and GLONASS constellations. The CNR value did not change much, equal too approx. 38-45 dBHz over time.

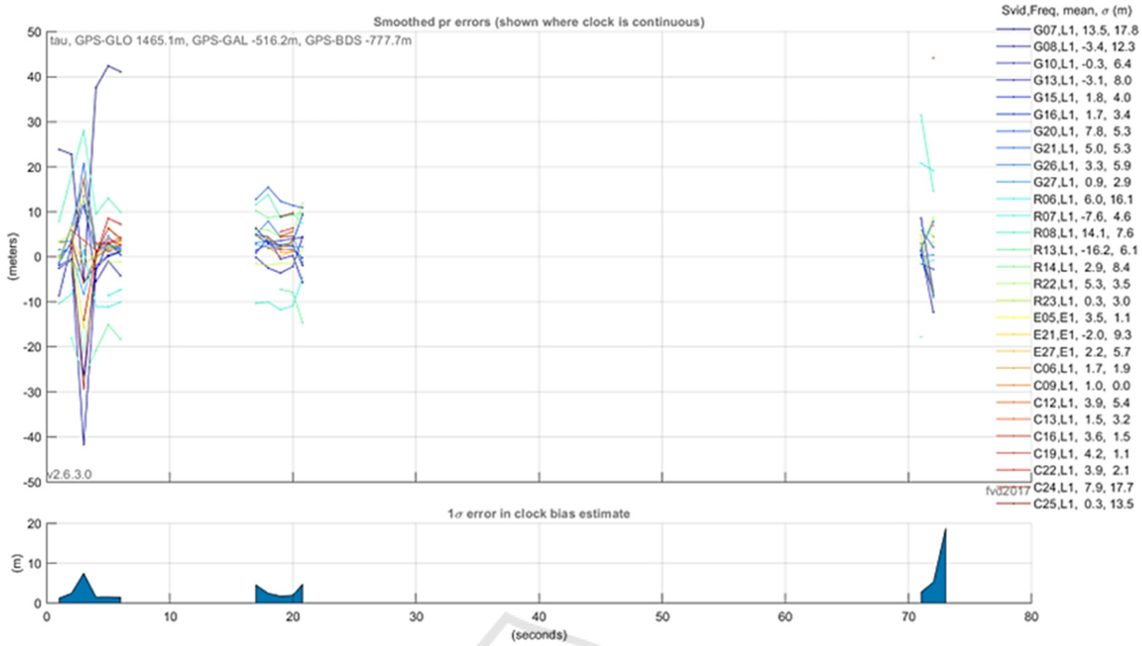

Figure 9: Pseudorange error – car excursion along the straight line route with Smartphone 1.

The frequency drift was equal to 0.04 ppb/s. The clock bias raised in a linear scale, up to 12 ms. The pseudorange error in case of 95% of data was less than 35.7 m. The pseudorange error oscillated around 0 m/s, and was getting higher for satellites on low elevation levels (see Figure 8).

In case of the WLS, the horizontal error for 50% of samples was less than 9.3 m, and less than 18.2 m for 95% of samples. The vertical error was equal to 16.1 m for 50% of samples, and 40.5 m for 90% of samples. The estimated height was equal to above 60 m, which was not close to real conditions, in which the height ranged for approx. 2 m. In case of raw data, the estimated height was around 0 m, with 40 m in just some cases.

4.7 Straight Line Route – Car Excursion with Smartphone 1

In case of BeiDou, the C19 satellite exceeded the reference signal level. However, the signal from this satellite was only observed for a limited time period.

The HDOP value ranges from 1.2 to 3. For GPS it indicated 7 to 11 objects, whereas in case of GLONASS, the number of monitored satellites ranged from 3 to 9.

During the evaluation, the clock was not stable, the maximum frequency drift was equal to 11.94 ppb. The clock drift was equal to 512 ppm. Due to clock biases, the pseudorange error in case of 95% of samples was less than 20.7 m. For Galileo, the error raised up to 100 m (see Figure 9). Thanks to WLS, the horizontal error for 95% of samples was less than 7.7 m, whereas for 50% it was less than 0.3 m.

4.8 Straight Line Route – Car Excursion with Smartphone 2

In case of GPS, those satellites had good geometry. HDOP during 63 s achieved a value of less than 1. Whereas, the number of observed satellites was equal to 10. The received signal strength level was stable, especially when examining GPS satellites at a height of above 30 degrees, i.e. G12.

During the whole time, the clock was stable, for the first 27 s the drift was relatively stable, increasing by 0.04 ppb/s. The clock bias was increasing linearly, reaching 4.5 ms at the end.

The pseudorange error for 95% of samples was less than 13.5 m (see Figure 10). This is mostly due to the fact that measurements were carried out in an open space. The Doppler shift error oscillated from 0 up to 3 m/s.

In case of WLS, the horizontal error for 95% of samples did not exceed 6.8 m, and was less than 3.3 m for 50% of samples. Whereas the vertical error, in case of 50% of samples, was less than 4.5 m, whereas for 95% of data it was less than 13.5 m. According to obtained results, for the first 40 s, the receiver (mobile device) was traveling on flat terrain, then the height decreased. However, this was not correct, as the height itself did not change.

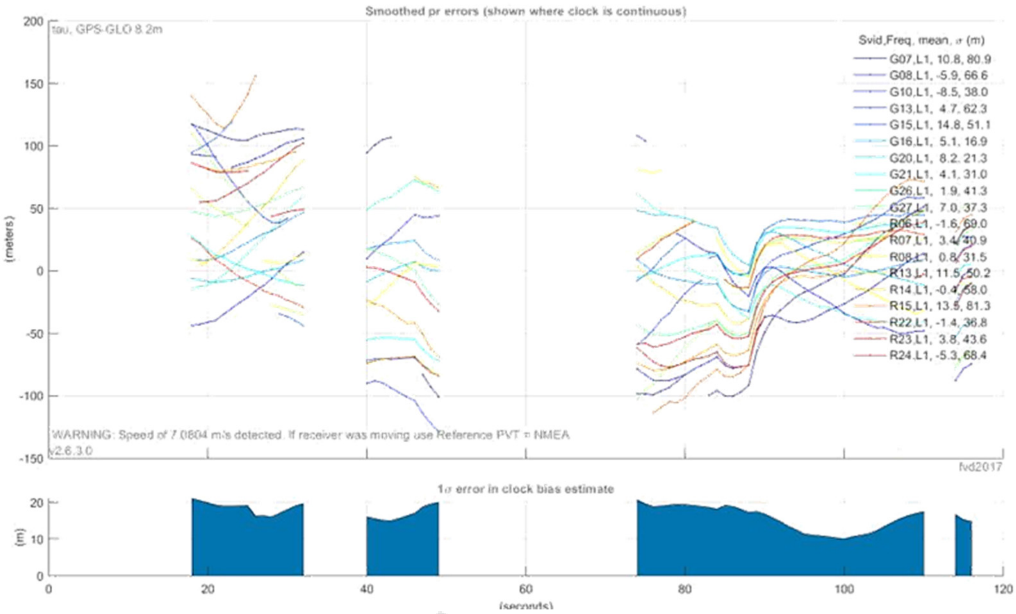

Figure 10: Pseudorange error – car excursion along the straight line route with Smartphone 2.

5 SUMMARY

This work describes results of a study, focused on the DOP and pseudorange precision of GNSS systems using smartphones, their quality, reliability, related to signal reception. The tested devices, coming from 2 different manufacturers, were all Android-powered devices. The measurement campaign itself was carried out in different conditions, including surrounding buildings, terrain topology, and urban fabric.

5.1 GNSS Signal Reception

The first smartphone seldom provided a signal level above the referenced CNR. Whereas the second one received at least over 10 such signals (above reference level), from which only 1 came from a constellation other than GPS or GLONASS.

The CNR value itself was also different. In case of Smartphone 1 this parameter dynamically changed (fluctuated) over time, even in a few second interval. On the other hand, Smartphone 2 proved to be more stable, as recorded CNR values did not changed that rapidly.

5.2 Time Calculations and Precision

One must note that maintaining continuity of clock (time) measurements is of great importance. In case of the second device, no discontinuous measurements were observed. In most cases, the frequency drift was equal to approx. 0.058 ppb/s. Whereas in case of Smartphone 1, during 26.6% of time, the measurements were discontinuous. In this case, most often the average frequency drift was equal to approx. 0.252 ppb/s. Furthermore in one case, it was not possible to calculate the drift due to instability.

With the utilization of the WLS algorithm, it was possible to calculate the pseudorange value. In case of Smartphone 1, the average value was equal to 31.82 m. Whereas for Smartphone 2, it was equal to 32.5 m. As shown, this difference was slight.

5.3 Overall Remarks

According to the study, it should be pointed out that numerous factors and conditions influence the final accuracy and precision of satellite positioning, especially in urbanized areas, when using different means of transport. The navigation performance depends on basic characteristics of the smartphone, both communication (e.g. antenna features, supported wireless systems, etc.) and data processing (CPU, RAM, storage, etc.). In such a context, it seems interesting to evaluate and compare in practice a broader range of mobile devices in future studies.

As noticed, more and more powerful consumer electronics are released on the market every year. On the other hand, user preferences and expectations do change from time to time (Finley et al., 2017; Falkowski-Gilski, 2020; Falkowski-Gilski and Uhl, 2020). Future studies should include consumer devices with diverse integrated GNSS modules, different distribution of the Android operating system, as well as deployment scenarios.

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