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PERFORMANCE ASSESSMENT OF KINEMATIC GNSS POSITIONING WITH SMARTPHONES BASED ON POST-PROCESSING OF RAW OBSERVATIONS

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ABSTRACT

In recent years, there have been significant technological advances in the development of common mobile devices. This brought progress also in the area of positioning with these devices. Allowing access to raw GNSS observations recorded by mobile devices opened possibilities to apply advanced positioning techniques in order to achieve higher positioning accuracy. The paper describes the results of kinematic measurements of a single-frequency Samsung Galaxy S10+ smartphone and a dual-frequency Samsung Galaxy Note10+ smartphone. Observations were repeatedly collected at a 1.76 km long test route in an urban environment at a pedestrian speed. Real-time positioning by autonomous method as well as collection of raw observations into RINEX format and their subsequent post-processing by differential techniques and Precise Point Positioning technique were realized. The achieved results were compared against a reference line representing the real trajectory and also against results of a geodetic grade GNSS receiver. Positioning accuracy of mobile devices ranged from the first decimetres to tens of metres, depending on the environment, tested smartphone and used post-processing technique. Dual-frequency smartphone Samsung Galaxy Note 10+ provided a better performance compared to the single-frequency device. Real-time positioning based on a simple autonomous technique and smoothing algorithm for route optimization reached lower positioning errors compared to all solutions based on collecting raw observations and their consequent post-processing with mentioned techniques.

Keywords: GNSS; Positioning; Post-processing; Smartphone.

1 INTRODUCTION

In 2016, mobile device users with Android 7.0 operational system firstly got an opportunity to access raw observations of Global Navigation Satellite System (GNSS) signals. Mobile applications that allowed the recording of these raw observations directly to a standard RINEX (Receiver Independent Exchange) data format were developed soon afterwards. In 2018, the first smartphone with a built-in dual-frequency GNSS receiver, the Xiaomi Mi8, was launched. Since then, many more dual-frequency smartphones from other manufacturers entered the market. All the technical development led to a significant increase of interest in advanced positioning with common smartphones and other mobile devices.

GNSS positioning can be performed in real-time or in post-processing mode. The first option provides user a knowledge of its position directly in the field. On the other hand, positioning based on post-processing requires an additional processing of raw GNSS data collected in the field in some specialized software. Recent progress in area of GNSS positioning with mobile devices is mainly related to the post-processing of raw observations, because, as reported in [1], there is currently no freely available application for the Android operating system that allows GNSS positioning by advanced real-time techniques such as Real-Time Kinematic (RTK).

RTK [2] is a long-used GNSS positioning technique popular e.g., in surveying, mapping, drones georeferencing. It represents a relative positioning utilizing mainly phase measurements and is based on corrections provided to the rover's position in real-time. These corrections are computed from observations realized at GNSS reference station with known exact position and are most often sent to rover via a mobile internet connection. The technique allows to reach positioning accuracy of several cm. Currently, the most commonly used is an implementation of Network RTK (NRTK) solution, where corrections for the rover are computed from the data of several reference stations located in its vicinity. NRTK allows to extend mean distances of reference stations in the network to about 50 to 70 km [3]. RTK technique is designed for kinematic solutions, therefore for applications when the rover position is continuously changing during the measurement. Therefore, the rover position is estimated for each measurement epoch, typically every second. If the relative positioning solution is implemented in post-processing mode instead of real-time, the positioning technique is typically referred to as Kinematic Difference Technique or Post-Processed Kinematic (PPK). Kinematic differencing technique was also tested in this study and is abbreviated as Kinematic in the texts below. Among the differential techniques, the classical differential GNSS (DGNSS) technique should also be mentioned. In contrast to the RTK technique, it is based only on code measurements. Its standard positioning accuracy is at the level of a few decimetres [2].

In recent years, interest in the non-differential technique called Precise Point Positioning [4,5] has been steadily increasing. The technique requires only one receiver and is very suitable for measurements in remote areas beyond the range of established GNSS reference stations. It can be seen as an advanced variant of standard autonomous technique where precise products with satellite ephemerides and satellite clock error corrections replace the broadcast navigation message and advanced models, and approaches are used for elimination of various effects and errors. Numerical least-squares approach or Kalman filtering is being used for an estimation of unknown parameters including receiver’s position. A certain amount of time after an initialization is required to achieve a high accuracy solution. This so-called convergence time typically lasts between 15 and 30 minutes. Integer ambiguity resolution in PPP is problematic compared to differential techniques due to uncalibrated phase delays [6]. With good quality precise products provided e.g., by the International GNSS Service (IGS) and the use of a geodetic receiver, it is possible to achieve a centimetre level positioning accuracy in static mode and a decimetre level in kinematic mode.

To date, several experts have dealt with accurate GNSS positioning via mobile devices. Banville and Van Digglen [7] were among the first who tested the quality of raw GNSS observations on smartphone. They used Samsung Galaxy S7 and tested only GPS signals. Their results of post-processing showed accuracy at the meter level. Lachapelle et al. [8] demonstrated that connecting Huawei P10 smartphone to an external geodetic grade GNSS antenna can improve the quality of raw observations and also increase the positioning accuracy. Netthonglang et al. [9] in their study focused on locating the phase centre of the GNSS antenna of Xiaomi Mi8 smartphone to improve the positioning accuracy because its position is not generally known unlike the position of the GNSS receiver. They found that the phase centre of the antenna is located at the top left of the smartphone (about 2.8 cm and 0.9 cm from the left and top, respectively). Bochkati et al. [10] addressed the same problem but tested three Xiaomi Mi8 smartphones. The results showed that even within a particular smartphone model, the phase centre of the antenna may not be the same.

After the first dual-frequency Broadcom BCM47755 chip entered the market in Xiaomi Mi8 smartphone in year 2018, interest in this area has grown further. Robustelli et al. [11] tested this smartphone in their study. The authors performed one-hour lasting static measurements first in an open area and then in a densely urbanized area. Collected raw observations were processed in RTKLIB software using the standard autonomous SPP (Single Point Positioning) technique. The results showed that utilizing Galileo signals on E5 frequency provided higher positioning accuracy and lower multipath errors than E1 frequency. Using a combination of GPS, GLONASS and Galileo signals led in some cases to better results than using GPS-only solutions. Gogoi et al. [12] tested Samsung Galaxy S8, Huawei P10 and Xiaomi Mi8 smartphones in single-frequency regime. They did a series of static measurements on the roof of a building and in an anechoic chamber to analyse an impact of multipath. In the anechoic chamber, they simulated L1 C/A signals of complete GPS satellite constellation in a controlled setup using a professional GPS signal generator. Collected raw observations were processed in MATLAB software. Standard deviation values of positioning errors were significantly smaller for all coordinate components for results from the anechoic chamber, with differences even in meters compared to the real environment on the roof.

More recently, Tomaštík et al. [13] tested five smartphones and two external mapping-grade GNSS receivers. A standard autonomous real-time positioning technique was used both in static and kinematic mode. Moreover, post-processing of raw observations was applied in some of tests. Testing sites were located in variable environments which included dense forests. The results showed that there was a gradual increase in positioning errors with increasing percentage of sky obstruction. Although performance of individual devices varied significantly, the only tested multi-frequency smartphone Xiaomi Mi8 provided more accurate and robust solutions compared with single-frequency smartphones.

Apart from post-processing of raw observations from smartphones, some authors tried to deal with real-time processing of raw observations with some advanced positioning technique. One of them were Dabove and Di Pietra [14] who mentioned as an important factor in their work that the user does not know if the recorded raw GNSS observations are being pre-filtered or not. In their study, two single-frequency smartphones, the Samsung Galaxy S8 Plus and the Huawei P10 Plus, were tested. Repetitive measurements in static mode were realized on roof of a selected building at the Politecnico di Torino University. Post-processing of the raw observations was performed in the open-source software RTKLIB and computed coordinates were compared with precise reference coordinates. Standard deviation (SDEV) values in the range of 4 - 9 cm were achieved by the mobile devices while using a self-developed program in MATLAB, which avoided filtering of raw observations and generated NRTK solution. Performance of the smartphones was compared to a low-cost u-blox EVK-M8T receiver equipped with a Garmin GA38 antenna. Under same conditions, this device achieved SDEV values only at the millimetre level. In another study, Li et al. [15] tested positioning accuracy of Huawei Mate30 and Huawei P40 smartphones placed on a dashboard and on a roof of a car driving in an urbanized area. They developed Android-based software for real-time kinematic positioning using the PPP technique. During the test measurements, they also performed a reference track recording with a geodetic receiver. The positioning results showed a horizontal Root-Mean-Square (RMS) errors in the range of 1 - 1.5 m with smartphones placed on the roof and better than 2.7 m at the 95th percentile with smartphones placed on the dashboard. For a complex review of fundamental works on using raw GNSS observations from smartphones for positioning, the reader is referred to study of Zangenehnejad and Gao [16].

Based on the results of above described or other works such as [17,18], it can be concluded that the accuracy of GNSS positioning via standard smartphones can currently range from tens of centimetres to tens of meters. Studies including testing of low-cost external GNSS receivers showed that these devices can provide a higher quality of positioning. With respect to previous studies, this paper tests two newer types of smartphones and compares their results with a geodetic grade GNSS receiver. Selected basic and advanced positioning methods are comprehensively evaluated. The work is based on kinematic positioning in an urban area realized by a pedestrian, therefore on a situation in which people often determine their location for mapping, navigation and other purposes. It is necessary to mention that most of the above-mentioned previous works were dealing only with the static measurements or realized the kinematic measurements with a car, meaning a different scenario compared to the pedestrian walk.

2 MATERIALS AND METHODS

In this section, information about tested devices, GNSS data collection and processing and methodology of results assessment are provided.

2.1 Tested devices

The goal was to test standardly available mobile devices with a single- and dual-frequency GNSS receiver, a reasonable price and Android operating system. Finally, two smartphones from Samsung manufacturer were obtained and tested. Their basic characteristics are provided in Table 1. Geodetic grade GNSS receiver Trimble R10 (see Table 2) was used as a reference device.

Table 1. Specification of the tested smartphones

Name	Samsung Galaxy S10+	Samsung Galaxy Note10+
OS	Android 9.0 (Pie)	Android 9.0 (Pie)
GNSS Chipset	Broadcom BCM47752 *(single-frequency)*	Broadcom BCM47755 *(dual-frequency)*
GNSS constellation and frequency	GPS (L1), GLONASS (L1), Galileo (E1), BeiDou (B1)	GPS (L1, L5), GLONASS (L1), Galileo (E1, E5a), BeiDou (B1)
Sensor	Fingerprint, accelerometer, gyro, proximity, compass	Fingerprint, accelerometer, gyro, proximity, compass, barometer, heart rate, SpO2

Table 2. Specification of the tested reference device

Name	Trimble R10
GNSS constellation and frequency	GPS (L1C/A, L1C, L2C, L2E, L5) GLONASS (L1C/A, L1P, L2C/A, L2P, L3) Galileo (E1, E5a, E5B) BeiDou (B1, B2) SBAS (L1C/A, L5)
Max precision RTK (Single Base < 30 km)	Horizontal: 8 mm + 1 ppm RMS Vertical: 15 mm + 1 ppm RMS
Max precision Network RTK	Horizontal: 8 mm + 0.5 ppm RMS Vertical: 15 mm + 0.5 ppm RMS

2.2 Experiment setup

Testing route was located in campus of the VŠB-Technical University of Ostrava and is shown in Figure 1. Level of sky view differed over the route, from places with almost no obstacles to places with high buildings or dense vegetation nearby the route or even two underpasses with a complete blockage of sky view. The total length of the route is 1.76 km.

The GNSS reference station named VSBO situated on the roof of the university rectorate was used in post-processing solutions utilizing differential techniques. VSBO belongs to the Czech national network of GNSS reference stations called CZEPOS (http://czepos.cuzk.cz/).

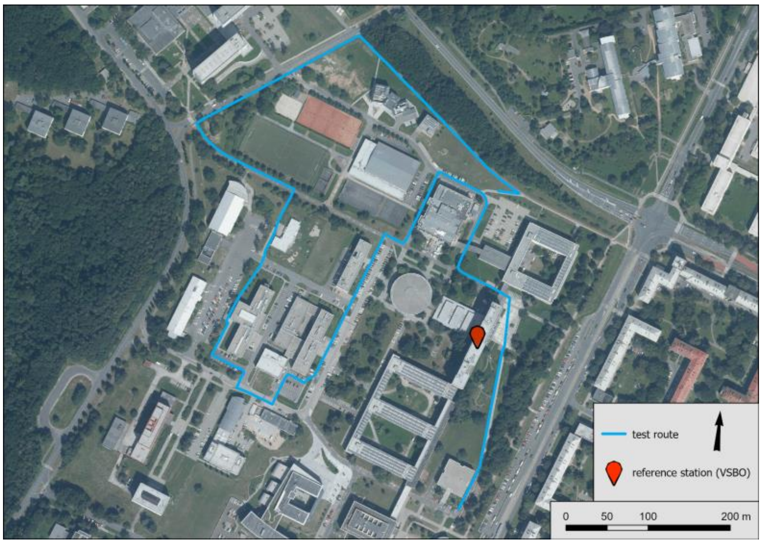

Figure 1. *Testing route and position of the VSBO GNSS reference station*

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2.3 Data collection

All test measurements were performed over four days as described in Table 3. The first two campaigns took place in early summer of 2021 and the second two campaigns in the vegetation-free period in the autumn of 2021. In total, four observation campaigns were realized on the described route. They took place on different days and at different times of the day to ensure conditions with a different satellite constellation. At the beginning of each campaign, all the devices were kept static at the starting point of the route for a minimum of 15 minutes to allow their complete initialization. All the measurements were realized with a speed of standard pedestrian walking. During repeated campaigns, the aim was to replicate the route as closely as possible and to maintain the same walking pace as in case of the first campaign. Photo documentation of the more complicated sections of the route was taken and used to find any differences from the original route. Identified differences were not neglected in the consequent processing. The way in which they were taken into account is described in section 2.5. During all measurements, tested mobile devices and the reference geodetic receiver were installed on a standard geodetic pole (see Figure 2).

Table 3. *Date and evaluated time of individual testing data collection campaigns in year 2021*

Date	Evaluated time period (hh:mm)	Length of period (minutes)
June 11	8:55–9:23	28
June 15	12:52–13:17	25
November 16	16:18–16:49	31
November 18	13:08–13:39	31

Figure 2. *Illustration of smartphone and reference receiver positions during data collection*

GnssLogger, rinex ON and Geo++ RINEX Logger applications were considered for collecting raw GNSS observations. During testing of the rinex ON application, an incorrect record of pseudoranges for GLONASS satellites into the RINEX file was identified. According to extremely large values of the pseudoranges, satellites would be located far beyond the position of the orbits. Also, the pseudorange values were not separated from the

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satellite identification marks. The remaining two applications GnssLogger and Geo++ RINEX Logger worked as expected.

Finally, the Geo++ RINEX Logger application was used to collect raw GNSS observations during the campaigns because it consumed less power compared to the GnssLogger application when tested. The latest version of Geo++ RINEX Logger 2.1.6 was installed on the dual-frequency smartphone Samsung Galaxy Note10+. On the second smartphone Samsung Galaxy S10+ an older version of the application 2.0.0 was used because the version 2.1.6 periodically let to interruption of data collection after a short period of time. Reason of this behaviour was not identified. The older version 2.0.0 did not support the BeiDou satellite system. For this reason, BeiDou system was excluded from all post-processing to ensure the same conditions for all the tested devices.

The Ultra GPS Logger application was used for real-time positioning. The application allowed the coordinates to be recorded in GPX (GPS Exchange) format at regular time intervals.

2.4 GNSS Data Post – Processing

Software RTKLIB (https://rtklib.com/) [19] was used for all post-processing of collected raw GNSS data. It is an open-source program package developed for multi-GNSS navigation and positioning and supports a wide range of differential and non-differential positioning techniques. Since the development of the official RTKLIB software in recent years is somehow limited, the RTKLIB explorer (http://rtkexplorer.com/) in version demo5 b34a was used in our case. It is a version of the RTKLIB optimized for low-cost receivers and is continuously being developed.

Table 4 contains basic information about the applied strategy for GNSS post-processing and used products and models. Information about all the tested positioning techniques and their settings are provided in Table 5.

An issue with phase measurements collected by the single-frequency smartphone Samsung Galaxy S10+ was found during data checks. The phase measurements stored in RINEX files had very unexpected values, often with a negative sign. Since the phase measurement data collected by the other smartphone with a newer version of the Geo++ RINEX Logger were correct, the problem could have been caused either by the device itself or by the older version of the logger.

Table 4. *Applied strategy and used products for post-processing of GNSS observations*

Precise products	Rapid multi-GNSS products from CODE [20]
Frequency	GPS (L1, L5), GLONASS (L1), Galileo (E1, E5a)
Strategy	Extended Forward Kalman Filter
Ionosphere	Global ionospheric map or Ionosphere-free linear combination or Broadcast
Troposphere	Saastamoinen model [21] or Zenith Total Delay (ZTD) estimation epoch-wisely
Antenna model	IGS14
Differential code bias	CODE DCB monthly product
Observation sampling rate	1s
Elevation mask	7°
Constellation combination	GRE (GPS/GLONASS/Galileo)

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Table 5. *Tested variants of post-processing of raw observations*

<table>
<tr><th>Processing variant</th><th>Devices</th><th>Frequency</th><th>Ionosphere correction</th><th>Troposphere correction</th><th>Satellite product</th></tr>
<tr><td colspan="6">PPP Kinematic technique</td></tr>
<tr><td>1</td><td>Trimble R10
Samsung Galaxy Note10+</td><td>L1+L5</td><td rowspan="2">Global ionospheric map</td><td rowspan="2">Estimated ZTD</td><td rowspan="2">Precise product</td></tr>
<tr><td>2</td><td>Samsung Galaxy S10+
Samsung Galaxy Note10+</td><td>L1</td></tr>
<tr><td colspan="6">DGNSS a Kinematic techniques</td></tr>
<tr><td>3</td><td>Trimble R10
Samsung Galaxy Note10+</td><td>L1+L5</td><td rowspan="2">Broadcast</td><td rowspan="2">Saastamoinen model</td><td rowspan="2">Broadcast</td></tr>
<tr><td>4</td><td>Samsung Galaxy S10+
Samsung Galaxy Note10+</td><td>L1</td></tr>
</table>

2.5 Evaluation Methodology

Evaluation of positioning accuracy of individual kinematic measurements was realized in two variants:

2.5.1 Calculation of differences between a reference digitized route and obtained positions

Reference lines representing an actual trajectory were created on the basis of an official aerial ortophotomosaic and self-obtained photographic documentation. One reference line was prepared for each observation campaign in order to avoid any influence of the assessment due to differences between individual actual trajectories. Using a reference line created from an independent data source allowed a comparison of geodetic grade receiver with both smartphones. One point layer was obtained per each post-processing technique, tested device and observation campaign combination. The shortest distance between the corresponding reference line and each point in the layer was calculated and consequently statistically evaluated.

The presented evaluation variant has two disadvantages: firstly, it allows only an evaluation in the horizontal component of coordinates and not in height. Secondly, recording time of the points is not taken into account since just the shortest distance to the reference line is calculated. This may result in the calculation of a distance to a different part of the reference line compared to reality.

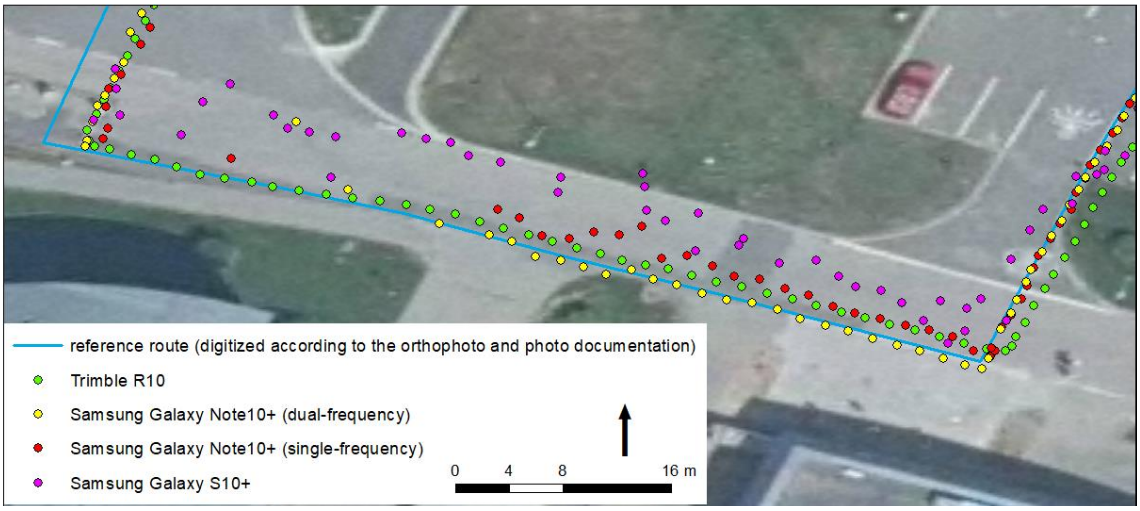

Figure 3. *Illustration of individual positions of GNSS devices and the digitized reference line*

2.5.2 Calculation of differences between positions obtained by the geodetic receiver and tested smartphones

Positions of the geodetic GNSS receiver were considered as the reference in case of this evaluation variant. Since all outputs contained individual points with their time stamp at 1s interval, it was possible to compare positions obtained by the devices at the same time. To be more specific, 3D distances between corresponding points were calculated. An obvious disadvantage of this evaluation variant is that it omits all positioning errors of the geodetic GNSS receiver. Still, based on the results of the first variant of evaluation, positioning errors of the geodetic GNSS receiver are at least of an order of magnitude lower than positioning errors of the smartphones.

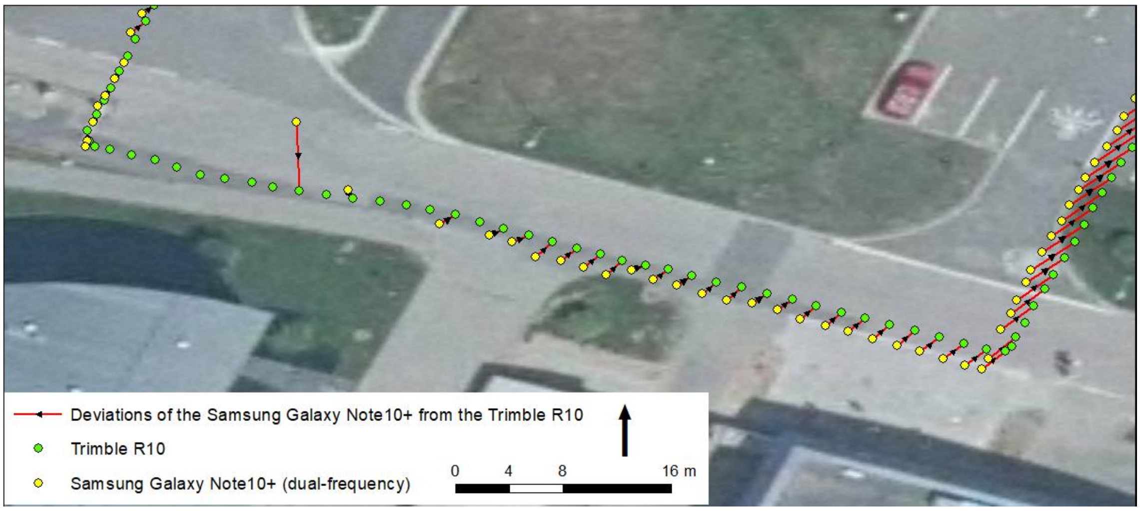

Figure 4*. Illustration of the evaluation variant based on calculation of differences between the geodetic grade GNSS receiver and tested smartphones*

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3 RESULTS

Apart from studying the positioning accuracy, an evaluation of number of observations collected by individual devices during the measurements was realized. Its detailed results are presented in Appendix A. Interestingly, the single-frequency smartphone Samsung Galaxy S10+ showed a higher mean number of code measurements at the L1/E1 frequency than both the dual-frequency smartphone Samsung Galaxy Note 10+ (+30.0%) and the geodetic Trimble R10 (+29.0%). In some of observation campaigns, the Samsung Galaxy Note 10+ smartphone managed to record slightly more code observances at the L1/E1 frequencies than the Trimble device. However, on L5/E5a frequency, it provided -18.7% less code observations compared to the geodetic receiver. In terms of phase observations, Trimble R10 was able to collect much more observations, as the Samsung Galaxy Note 10+ gathered -30.7% observations at L1/E1 and even -48.7% at L5/E5a.

3.1 PPP

First, the results of post-processing with the PPP kinematic technique are presented in Table 6 and Table 7. Parameter completeness of positioning provides information about a percentage of epochs in the whole kinematic measurement, for which the particular positioning solution was computed. It can be noticed that for the tested devices, where the solution was computed for a larger number of epochs, it was possible to observe simultaneously a higher achieved accuracy. This applies both for mean distances as well as for standard deviation (SDEV). The Samsung Galaxy Note10+ smartphone using dual (single) frequencies managed to calculate 10.0% - 21.6% (11.7% - 24.8%) fewer points on the route compared to the Trimble R10. Even a more significant drop in number of available points compared to the Trimble R10 (35.5% - 53.3%) was found for the single frequency smartphone Samsung Galaxy S10+.

A clear dominance of the Trimble R10 was apparent also in the positioning accuracy with standard deviations ranging from tens of centimetres to 1.5 meters. From the tested smartphones, the best performance was provided when processing dual-frequency data collected by the Samsung Galaxy Note10+. It is apparent from the provided statistical evaluation and also from route visualizations shown in the Appendix B. Increase of standard deviations and mean distances for the single frequency processing of this device compared to the dual frequency results was typically at the level of decimetres or first meters. The second tested smartphone provided much worse results with statistics mostly exceeding 10 meters. This situation is most probably due to above-described issues in the collection of phase measurements.

Table 6. *Results of post-processing with the PPP technique (variants of post-processing with numbers 1 and 2, see Table 5, variant of evaluation n. 1, see section 2.5)*

	Trimble R10	Samsung Galaxy Note 10+ (L1+L5)	Samsung Galaxy Note10+ (L1)	Samsung Galaxy S10+
SDEV (m)	0.59–1.42	2.91–4.97	3.10–6.82	8.86–14.82
Mean horizontal distance (m)	0.71–2.04	2.15–3.34	2.95–3.58	6.28–10.86
Completeness of positioning (%)	97.7–100.0	78.1–88.4	74.9–87.4	38.1–63.4

Table 7. *Results of post-processing with the PPP technique (variants of post-processing with numbers 1 and 2, see Table 5, variant of evaluation n. 2, see section 2.5)*

	Samsung Galaxy Note 10+ (L1+L5)	Samsung Galaxy Note10+ (L1)	Samsung Galaxy S10+
SDEV (m)	4.45–7.22	4.78–9.07	12.99–21.79
Mean 3D distance (m)	2.92–4.94	4.54–5.29	12.15–19.30
Completeness of positioning (%)	77.7–88.3	74.7–87.4	46.9–63.22

3.2 DGNSS

Results for the first (second) variant of evaluation for the DGNSS technique are available in Table 8 (Table 9), respectively. Compared to the PPP kinematic technique, both smartphones were able to be reach a higher number of epochs in which the positioning was available with the DGNSS technique. The difference was significant mainly in case of the Samsung Galaxy S10+ smartphone which had issues with collection of the phase measurements. Unfortunately, the positioning errors of this single-frequency smartphone stayed very high, with SDEV vales in the first evaluation technique ranging around 9 m and mean distances around 8 m. The corresponding statistical parameters reached by the dual frequency smartphone were about 20 to 60 percent lower, meaning a better positioning performance. Results obtained when processing dual-frequency observations were again better than the single-frequency ones. In this case, the differences between single- and dual- frequency solutions were not so apparent in the visual evaluation available in Appendix C. The geodetic Trimble R10 receiver delivered SDEV around 0.7 m and mean distances around 0.8 m, quality of its positioning was therefore much better compared to the common mobile devices.

Differences between routes reconstructed from post-processing of raw observations with PPP Kinematic and DGNSS techniques are well visible in their visualization (see Appendix B and Appendix C). PPP Kinematic offered much smoother trajectories in places with a good visibility on the sky.

Table 8. *Results of post-processing with the DGNSS technique (variants of post-processing with numbers 3 and 4, see Table 5, variant of evaluation n. 1, see section 2.5)*

	Trimble R10	Samsung Galaxy Note 10+ (L1+L5)	Samsung Galaxy Note10+ (L1)	Samsung Galaxy S10+
SDEV (m)	0.52–0.66	3.31–5.86	4.77–7.51	8.34–9.73
Mean horizontal distance (m)	0.77–0.85	2.81–3.72	4.20–5.45	7.33–8.65
Completeness of positioning (%)	97.7–100.0	90.4–96.7	90.4–96.7	98.17–100.0

Table 9. *Results of post-processing with the DGNSS technique (variants of post-processing with numbers 3 and 4, see Table 5, variant of evaluation n. 2, see section 2.5)*

	Samsung Galaxy Note 10+ (L1+L5)	Samsung Galaxy Note10+ (L1)	Samsung Galaxy S10+
SDEV (m)	4.55–4.71	5.91–8.86	9.07–22.91
Mean 3D distance (m)	3.93–6.73	5.75–7.06	9.22–23.47
Completeness of positioning (%)	90.1–96.4	90.1–96.4	97.7–100.0

3.3 Kinematic

Results for the Samsung Galaxy S10+ smartphone achieved in post-processing with the differential Kinematic technique had to be excluded from the statistical evaluation. Although the solutions were achieved for a number of epochs comparable to both other tested devices, the computed trajectories showed extreme deviations from the real trajectories (see Appendix D). This situation was most likely caused by the afore-mentioned lack of proper phase measurements from the Galaxy S10+ smartphone which are necessary for the Kinematic technique.

All the results presented in Table 10 and 11 were achieved with float ambiguities. Turning on ambiguity fixing in the processing of observations collected by smartphones led to higher positioning errors and mainly to a significantly lower number of epochs for which the solution was computed. This was probably due to a rather poor quality of observations from smartphones and continuous interruptions in signal acquisition due to various obstacles around the testing route. Computing solutions based on float ambiguities led to more stable results.

Geodetic receiver Trimble R10 reached the lowest positioning errors right with the Kinematic technique based on float ambiguities. This is apparent from SDEV values below 50 cm as well as from the visualization of the route shown in the Appendix D. Still, the DGNSS technique was rather close to the results of the Kinematic technique.

Standard deviations of the dual-frequency smartphone varied in most cases only in the units of first meters. Compared to the DGNSS differential technique, an improvement at the level of decimetres or even the first meters can be observed in most of the results of the Kinematic processing of the Samsung Galaxy Note10+ smartphone. The only exception was found in results from the November 16, where SDEV values were about three times larger compared to those from all other three observation campaigns. This increase in SDEV was caused by a significant deviation from the reference trajectory in a few tens of meters long section (see Appendix D). In contrast to the previously presented positioning techniques, the dual-frequency processing did not provide better results compared to the single-frequency solutions. In some cases, the results of the single-frequency solutions even surpassed the dual-frequency ones.

Table 10. *Results of post-processing with the Kinematic technique (variants of post-processing with numbers 3 and 4, see Table 5, variant of evaluation n. 1, see section 2.5)*

	Trimble R10	Samsung Galaxy Note 10+ (L1+L5)	Samsung Galaxy Note10+ (L1)	Samsung Galaxy S10+
SDEV (m)	0.45–0.48	2.27–8.38	2.53–7.31	–
Mean horizontal distance (m)	0.72–0.84	2.11–4.52	1.83–4.45	–
Completeness of positioning (%)	97.7–100.0	90.4–96.7	90.4–96.7	–

Table 11. *Results of post-processing with the Kinematic technique (variants of post-processing with numbers 3 and 4, see Table 5, variant of evaluation n. 2, see section 2.5)*

	Samsung Galaxy Note 10+ (L1+L5)	Samsung Galaxy Note10+ (L1)	Samsung Galaxy S10+
SDEV (m)	2.99–16.11	5.22–14.04	–
Mean 3D distance (m)	2.36–6.47	3.67–7.10	–
Completeness of positioning (%)	90.1–96.4	90.1–96.4	–

3.4 Autonomous technique

Real-time positioning of smartphones realized in the Ultra GPS Logger application with the simple autonomous technique achieved significantly lower values of standard deviation (see Table 12 and Table 13) than recording of raw observations and their subsequent post-processing in RTKLIB. This is also evident from the visualization of the route shown in Appendix E. In the visualization of the Samsung Galaxy Note 10+ results from November 16, significantly larger deviations from the reference route can be seen in one segment. These were probably caused by the problematic observation conditions given by a passage below building and consequent part leading close to the 30 meters tall rectorate building. As can be seen, this segment had a smaller effect on the results of the Samsung Galaxy S10+ smartphone. Using evaluation variant n. 2, most measurements showed an increase in SDEV compared to evaluation variant 1 only in the first tens of centimetres for both single-frequency (0.25–0.62 m) and dual-frequency smartphones (0.27–0.39 m). This is thus a clear improvement compared to the results obtained by post-processing with advanced GNSS techniques, where there was an increase between the first and the second evaluation variant up to several meters. Mean distances from the reference line represented by the digitised route (see Table 12) were in most cases in the range of 1–2 metres, which is also a significant improvement compared to the results of post-processing with differential techniques.

After these findings, developers of the Ultra GPS Logger were contacted with a question if the application was applying some smoothing algorithm. It was found out that an optimization algorithm based on Kalman filter is implemented in the application in order to improve quality of the positioning. There is therefore a significant difference in this type of positioning compared to the techniques implemented in the RTKLIB which do not apply any kind of route optimization and are only estimating the receiver's position in every epoch from the available satellite observations.

Table 12. *Real-time positioning results via Ultra GPS Logger application (variant of evaluation n. 1, see section 2.5)*

	Samsung Galaxy Note 10+ (L1+L5)	Samsung Galaxy S10+
SDEV (m)	1.16–4.39	1.04–2.09
Mean horizontal distance (m)	1.25–2.11	1.20–1.91
Completeness of positioning (%)	90.6–100.0	97.5–100.0

Table 13. *Real-time positioning results via Ultra GPS Logger application (variant of evaluation n. 2, see section 2.5)*

	Samsung Galaxy Note 10+ (L1+L5)	Samsung Galaxy S10+
SDEV (m)	1.47–4.66	1.53–2.38
Mean 3D distance (m)	1.88–3.29	1.89–2.87
Completeness of positioning (%)	91.9–100.0	98.0–100.0

4 DISCUSSION AND CONCLUSION

GNSS raw observation data from two Samsung smartphones were collected and post-processed with three advanced GNSS techniques in order to evaluate their positioning performance. A set of kinematic measurements on 1.76 km long route through various environments was realized in a mode of pedestrian walking. Besides collecting raw observations for the consequent post-processing, real-time positioning was realized in the Ultra GPS Logger application.

In general, the positioning accuracy of mobile devices ranged from the first decimetres to tens of metres, depending on the environment, tested smartphone and used post-processing technique. The results clearly showed that mobile devices cannot compete with a geodetic grade GNSS receiver, both in terms of positioning accuracy and precision. Both smartphones had also issues with a collection of phase measurements. As already mentioned above, phase measurements were not properly recorded by the single-frequency Samsung Galaxy S10+ and there was a significant drop in number of phase measurements gathered by the dual-frequency smartphone Samsung Galaxy Note 10+ compared to the geodetic grade receive.

Samsung Galaxy Note 10+ provided visibly better positioning performance compared to the Samsung Galaxy S10+, even in solutions where only L1/E1 signals from the dual-frequency device were utilized. However, this situation was true only when raw observations were collected and lately post-processed in RTKLIB. In tests based on real-time positioning in the Ultra GPS Logger application, both smartphones reached similar performance, the single-frequency device Samsung Galaxy S10+ was even better in terms of standard deviation. Its worse results in post-processing scenarios were therefore probably caused by described issues related to raw observations collection with the older version of the GEO++ RINEX Logger application.

Real-time positioning in Ultra GPS Logger based on simple autonomous technique and smoothing algorithm for route optimization led to standard deviations between 1 and 4 m, therefore to much lower values than in case of all three tested post-processing positioning techniques. For kinematic solutions with smartphones, using real-time positioning with a proper kind of route optimization can be therefore recommended over the post-processing of raw observations with differential techniques or PPP without any application of route optimization.

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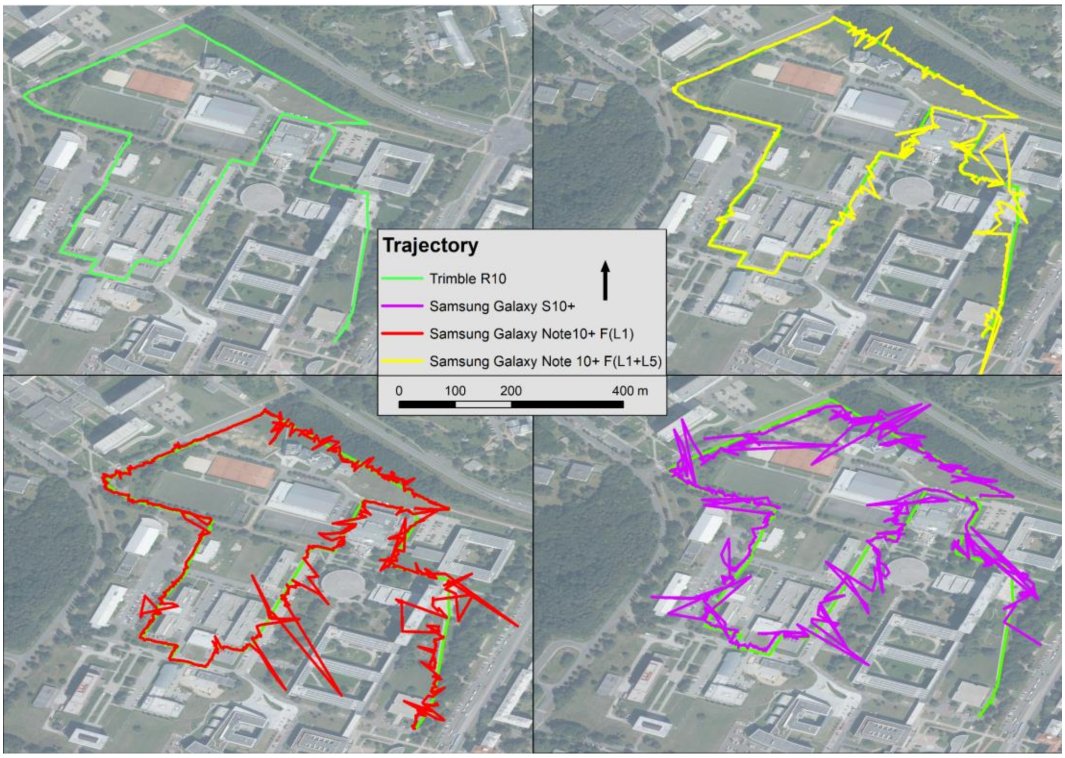
APPENDICES

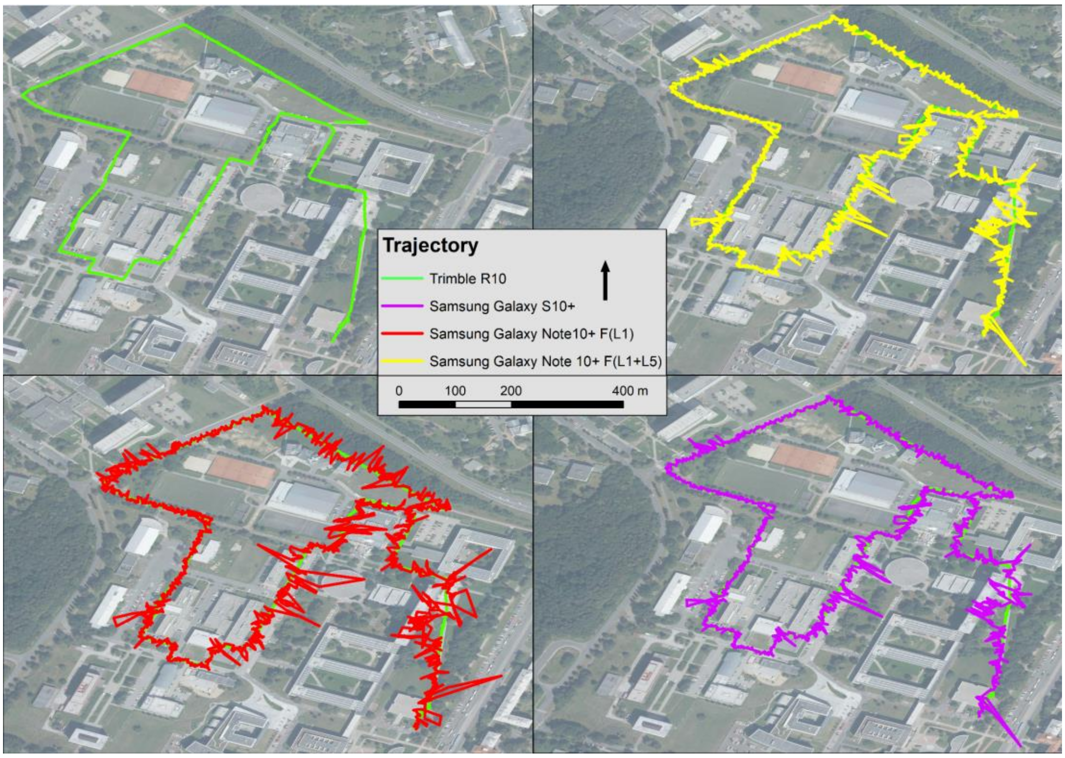
Appendix A. *Number of GNSS observations collected by individual devices during all four observation campaigns on the test route*

Date, time	Device	Measurement type	Frequency	Number of observations			
				GPS	**GLONASS**	**Galileo**	**Total**
June 11 8:55–9:23	Trimble R10	code	L1/E1	10233	8245	8803	**27281**
			L5/E5a	3949	–	7791	**11740**
		phase	L1/E1	9124	8114	8640	**25878**
			L5/E5a	4078	–	8035	**12113**
	Samsung Galaxy Note10+	code	L1/E1	14370	6554	9223	**30147**
			L5/E5a	2412	–	7759	**10171**
		phase	L1/E1	9358	4313	7552	**21223**
			L5/E5a	1611	–	5563	**7174**
	Samsung Galaxy S10+	code	L1/E1	15329	13355	8582	**37266**
June 15 12:52–13:17	Trimble R10	code	L1/E1	10814	7580	9872	**28266**
			L5/E5a	7079	–	8474	**15553**
		phase	L1/E1	10814	7580	9872	**28266**
			L5/E5a	7082	–	8474	**15556**
	Samsung Galaxy Note10+	code	L1/E1	11655	2631	8471	**22757**
			L5/E5a	5144	–	6585	**11729**
		phase	L1/E1	8241	1742	6439	**16422**
			L5/E5a	3967	–	4498	**8465**
	Samsung Galaxy S10+	code	L1/E1	14458	10080	12059	**36597**
November 16 16:18–16:49	Trimble R10	code	L1/E1	14168	7472	9097	**30737**
			L5/E5a	4983	–	8359	**13342**
		phase	L1/E1	14168	7472	9097	**30737**
			L5/E5a	4985	–	8359	**13344**
	Samsung Galaxy Note10+	code	L1/E1	16468	4758	10019	**31245**
			L5/E5a	2845	–	7590	**10435**
		phase	L1/E1	10038	2844	7087	**19969**
			L5/E5a	1415	–	4164	**5579**
	Samsung Galaxy S10+	code	L1/E1	19948	13016	14046	**47010**
November 18 13:08–13:39	Trimble R10	code	L1/E1	14902	5946	10609	**31457**
			L5/E5a	5569	–	9433	**15002**
		phase	L1/E1	14902	5946	10609	**31457**
			L5/E5a	5569	–	9433	**15002**
	Samsung Galaxy Note10+	code	L1/E1	16388	5492	10566	**32446**
			L5/E5a	4337	–	8379	**12716**
		phase	L1/E1	10921	3574	8224	**22719**
			L5/E5a	2446	–	5011	**7457**
	Samsung Galaxy S10+	code	L1/E1	19919	12279	13990	**46188**

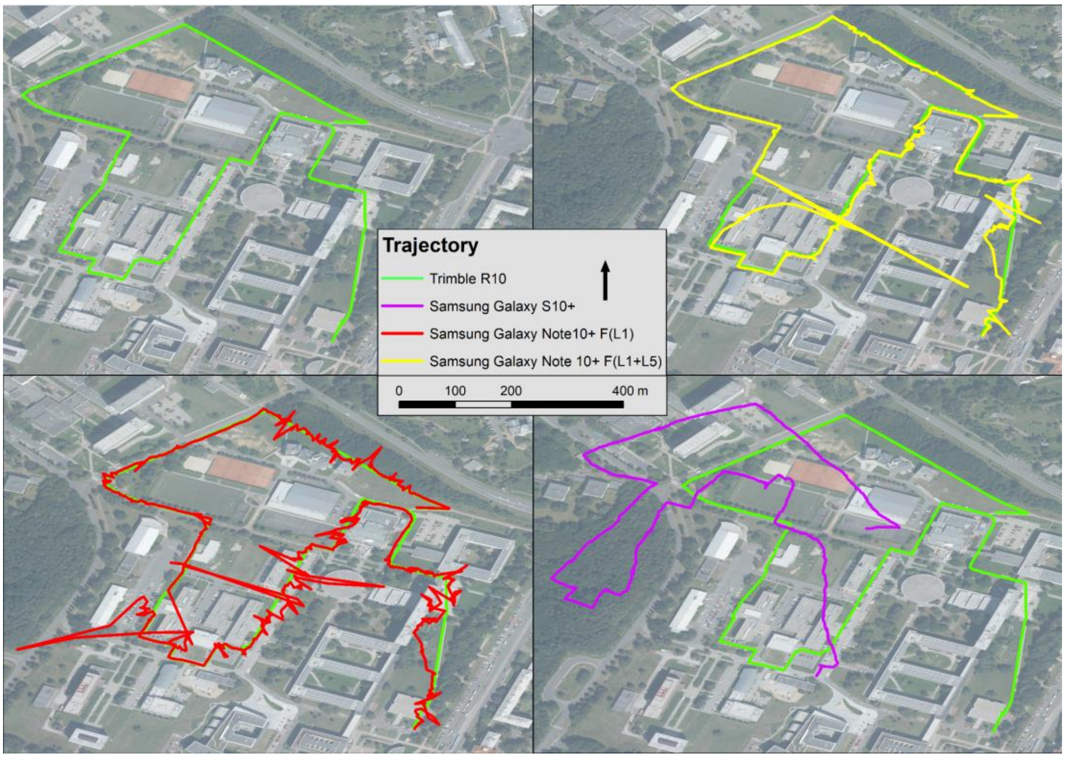
***Appendix B**. Estimated routes of tested devices using the PPP kinematic technique on November 16 (variants of post-processing with numbers 1 and 2, see Table 5)*



***Appendix C.** Estimated routes of tested devices using the DGNSS technique on November 16 (variants of post-processing with numbers 3 and 4, see Table 5)*



Appendix D. *Estimated routes of tested devices using the Kinematic technique on November 16 (variants of post-processing with numbers 3 and 4, see Table 5)*



Appendix E. *Mapped routes of the tested devices using the Ultra GPS Logger application on June 15 (up), November 16 (down)*

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