Positioning Performance Evaluation of a Dual Frequency Multi-GNSS Smartphone

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Abstract. Smartphones with dual-frequency multi-constellation GNSS (Global Navigation Satellite Systems) receivers are now available on the market. This study examines their usage in simple surveying tasks, such as data acquisition for GIS, e.g. for a tree cadastre, lantern cadastre, traffic signs, etc., as well as line documentation, such as for underground power lines. For the experiments, the Pixel 5 from the manufacturer Google LLC is chosen. Code and phase observations are recorded in different scenarios. Evaluation in post-processing based on these observations in Single Positioning (SPP) and Precise Positioning (PPP) mode are carried out. In the analyses, the main focus is led on the achievable positioning accuracies and resulting deviations from reference points serving as ground truth. Apart from these parameters, other criteria, such as the measurement effort and costs, quality, accuracy and repeatability of the measurements are investigated. The results of the experiments indicate that the Pixel 5, although it enables the recording of satellite data on two frequency bands, can only be used to a limited extent in practical surveying tasks because it does not meet the accuracy requirements on the centimeter level. The main reason for this is the quite low quality of the observations. With long observation times, however, results with a positioning accuracy of less than half a meter are achievable with the smartphone. Thus, the Pixel 5 is capable to achieve the requirements in terms of positioning accuracy and reliability for applications such as data acquisition for Geographic Information Systems (GIS) and especially in Location-based Services (LBS).

Keywords. GNSS dual-frequency measurements, smartphone, positioning accuracies assessment, Single Point Positioning (SPP), Precise Point Positioning (PPP), static observations, stop-and-go and kinematic measurements.

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1. Introduction

Due to recent developments in the last years in the smartphone market, some smartphone models are nowadays available providing multi-constellation GNSS with signals on two frequency bands (see e.g. Barbeau, 2018; Darugna, 2021). They are also capable to record the raw data of the GNSS signals, which facilitates high performance real-time and post-processing applications. Thus, using these new models more precise positioning with GNSS has become possible. In this study, it is analysed if simple tasks of applied surveying, GIS (Geographic Information System) data acquisition or in LBS can be performed with these smartphones. Their usage saves time and cost, since no additional hardware has to be purchased, such as PDAs or dedicated GIS receivers. One current smartphone is selected for the experiments. It is the Pixel 5 of the American manufacturer Google LLC, which has been available since October 2020.

For the experiments, measurements were carried out on the roof of the Electrical Engineering Institute (EI) building of the TU Wien (Vienna University of Technology) and in a park in front of the main building (i.e., Karlsplatz). In some of the tests the smartphone is placed on a coordinative known reference point, i.e., a measuring pillar on the building roof or at known points of the control network available on Karlsplatz. Furthermore, measurements at Karlsplatz were performed in stop-and-go and kinematic mode where a user with the smartphone held in his hand walked along a straight trajectory with usual walking speed. The main purpose of the experiments is the analysis of the achievable positioning accuracies. The stop-and-go and kinematic measurements are used to simulate real measurement tasks such as data acquisition for GIS, such as for a tree cadastre, lantern cadastre, traffic signs, etc., as well as line documentation, such as for underground power lines.

The paper is structured as follows: In section 2 the characteristics of the Google Pixel 5 smartphone and the basics of the chosen approach for the investigations are presented. Also the fundamentals of the positioning methods are reviewed. This is followed by comprehensive analyses of the observations carried out in the experiments in section 3. Here firstly the GNSS satellite availability and quality, then the results for static observations using the Single Point Positioning (SPP) and Precise Point Positioning (PPP) methods and the stop-and-go and kinematic measurements along the straight trajectory are presented in section 3.1 to 3.3, respectively. Section 4 summarizes the main findings and concludes the paper.

2. Basics and Approaches

2.1. Smartphone Basics

The Google Pixel 5 smartphone incorporates a Snapdragon 765G processor from Qualcomm which allows the recording of multi-GNSS signals on two frequencies (Qualcomm, 2019). Table 1 provides an overview of the supported satellite positioning systems and frequencies. As can be seen dual frequency operation is available for the US Navstar GPS, European Galileo and Japanese QZSS (Quasi-Zenith-Satellite-System) satellite based augmentation system. For data logging an App from Geo++ GmbH, Germany, was used. The App is based on the freely accessible source code of Google's GPS Measurement Tool. With this App, raw GNSS observations in RINEX (Receiver Independent Exchange Format) format from the smartphone can be recorded. Figure 1 shows a snapshot of the interface of the GNSS logger. The RINEX Logger can record signals of all GNSS listed in Table 1. Apart from QZSS, other augmentation systems such as the European Satellite Based Augmentation System (SBAS) called EGNOS (European Geostationary Overlay System) are not supported.

GPS	L1 / L5
Glonass	R1
Galileo	E1 / E5a
Beidou	B1
QZSS	L1 / L5

Table 1. : Supported GNSS and their useable frequency bands for the Google Pixel 5.

The measurements took place on the roof of the building of the TU Wien in the Gußhausstraße campus and on the nearby Karlsplatz. Eleven measuring pillars are located on the roof, the coordinates of which are known. On Karlsplatz there is a control point network.

In addition, a geodetic GNSS receiver from Spectra Geospatial, the SP80, is used as a reference station and placed in 12 meter distance from the smartphone on a second measuring pillar on the roof of the EI building. Figure 2 shows the set-up on the roof in the three pictures on the left. The SP80 receiver is capable to record GPS (L1, L2, L5) and GLONASS (R1, R2) data. In order to be able to use them, they are then converted to the RINEX format. The RINEX Converter 4.7.2 from Trimble is used for this conversion. Further data, such as the satellite ephemeris (RINEX navigation file) and clock corrections, are acquired from the CORS network

EPOSA (see EPOSA, 2021) and the IGS (International GNSS Service). Post-processing of the raw data is carried out with the freely available Real Time Kinematic Library (RTKLib) software package. Furthermore Matlab routines are used to eliminate outliers, to calculate statistical parameters and transformations between different reference systems, such as from the WGS84 (World Geodetic System 1984) of GPS and the ETRS89 (European Terrestrial Reference System 1984).

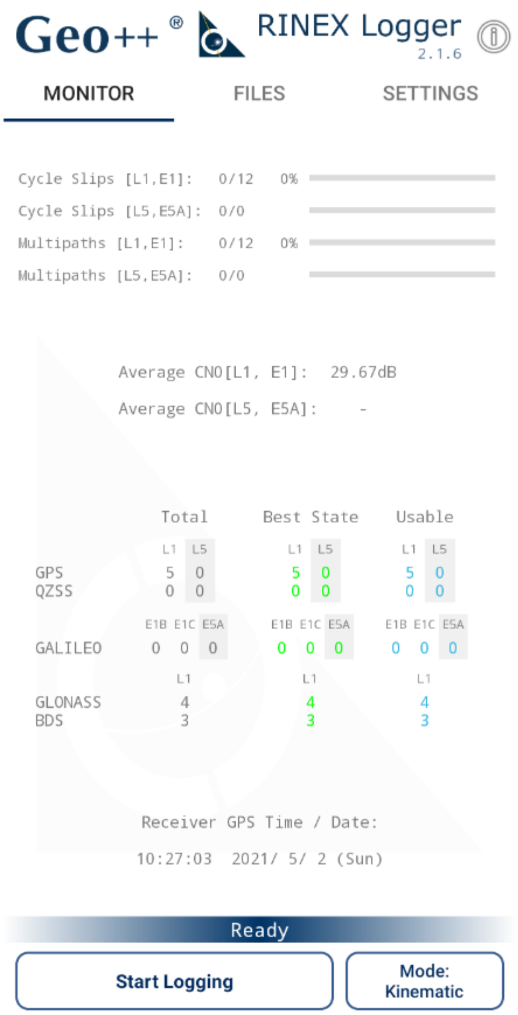

Figure 1. Interface of the Geo++ RINEX logger.

RTKLib includes positioning algorithms for all common GNSS systems. In addition to the evaluation of the data in post-processing, the software can be used for positioning in real-time. In the course of this work, however, only the post-processing applications are used. The software package contains several subroutines. In this work, we use the applications RTKPlot and RTKPost. With RTKPlot, observations, navigation data and the solutions calculated with RTKPost can be visualized. In RTKPost the actual processing of the data takes place. The software includes different positioning methods. The methods Single Point Positioning (SPP), Precise Point Positioning (PPP)and the method static are used to calculate baselines.

Figure 2. Smartphone und reference receiver SP80 on two neighbouring measuring pillars on the roof of the EI building of TU Wien and mobile measuring set-up on Karlsplatz.

2.2. Single Point Positioning (SPP)

Positioning with the help of SPP is an absolute position determination method. The position is determined by code observation; for civil users with PRN (Pseudo-random Noise) code C/A (Coarse Acquisition). The satellites permanently transmit their position in the form of their orbit data and the current time. These signals are modulated on a specified carrier frequency with an individual PRN code for each satellite and transmitted via it. This allows them to be received and demodulated by a receiver on Earth (Reußner, 2016). Since the speed at which the signal travels there is a time difference between the actual time at the time when the signal is received and the time sent by the satellite. This difference is the signal travel time. Since the receiver clock is not synchronized with the satellite clock in practice and is usually not accurate enough, we speak of the pseudorange observation for the time being. From this the pseudorange or distance to the satellite can be calculated by multiplying it with the signal speed (approximately the speed of light). Three Cartesian coordinates (X, Y, Z) are required to define a position in three-dimensional space. Consequently, three observations or three satellite signals should suffice to identify these three unknowns. When positioning with GNSS, however, there is a fourth unknown: the receiver clock error. This is the difference between the receiver clock and the satellite clocks already mentioned. The measured signal travel times must be corrected for this error. In order to determine the clock error, a fourth observation is necessary. Thus, the signals of at least four satellites are needed to determine the four unknowns (3 position coordinates and receiver clock error). Mathematically speaking, a system of equations with four equations and four unknowns is solved (Reußner, 2016). Geometrically, the position determination can be described as follows: The distance of the receiver to the satellites can be calculated from the signal travel times. The position of the satellites is known via the orbit data of the satellites. This allows spheres to be placed with the distance as a radius around three of the satellites. The point at which the surfaces of the three spheres intersect corresponds to the position of the receiver. The accuracy of single point positioning is in the range of several meters.

2.3. Atmospheric Error Sources

In addition to satellite and receiver-specific errors such as orbit, hardware or clock errors, the atmosphere has a major influence on the accuracy of the determined positions (Reußner, 2016). To reach the receiver, the signals must pass through the atmosphere. This affects the propagation speed of the signals and thus their travel time. The signals are slowed down and no longer propagate at the speed of light. This atmospheric refraction is dependent on time and place. If the precise signal speed is not known, the distances to the satellites can only be determined very inaccurately. Consequently, the identified position of the recipient differs from the actual position. The effects of atmospheric refraction can be divided into the neutral atmosphere (tropospheric parts) and ionospheric parts.

The neutral atmosphere ranges up to an altitude of 90 km which are the ranges from the troposphere to the stratosphere to the mesosphere. The influence of the neutral atmosphere on the travel time depends on the meteorological conditions along the signal pathway and can be divided into hydrostatic (dry) and wet (or humid) fractions. Hydrostatic fractions account for 90% and wet fractions 10% of the tropospheric travel time delay. The hydrostatic components can be easily modelled on the Earth's surface using meteorological measurements (pressure and temperature) or through the use of standard atmospheric models and can therefore be modelled quite easily. For the wet fraction, the moisture content is largely determined by the water vapour content of the atmosphere along the signal path. This is subject to temporal and spatial fluctuations and is difficult to model (Reußner, 2016).

The neutral atmosphere is followed by the ionosphere. It passes into interplanetary space at an altitude of about 2000 km. The ionosphere contains the thermo- and exosphere. It contains large amounts of ions and free electrons, which significantly influence the delay of electromagnetic waves. The strength of this influence depends on the density of the free electrons along the signal path. To characterise this usually the parameter Total Electron Content (TEC) is used. Density, in turn, is influenced by the intensity of solar radiation and the geographic latitude and is subject to cyclical fluctuations. For example, the number of free electrons is ten times higher during the day than at night. The ionosphere is a dispersive medium for electromagnetic waves. This means that the propagation velocity depends on the frequency. This effect can be exploited to model the influence of ionospheric travel time delay. If the influence of the ionosphere is not eliminated, deviations in the order of several meters up to tens of meters for the measured pseudorange would occur. Although the satellites transmit several parameters modelling the state of the ionosphere, this non-negligible residual deviation remains. Dual-frequency observations can help in this respect as the ionosphere is dispersive. This means that the two frequencies travel with different propagation speed. Using the two frequencies recorded by the receiver linear combinations can be determined to reduce the effect of the ionospheric propagation travel time delays.

A further error influence is the multipath of the GNSS siganls. Through reflections on buildings, reflecting surfaces or other objects, a signal reaches the receiver in different ways. The direct signal is superimposed by the reflected signals which can cause interference. The received signals are time-delayed because the reflected portion has travelled a longer distance. Normally, the amplitudes of the reflected signals are lower than those of the direct signal. As the satellites move, the multipath effects also change over time (Reußner, 2016).

The dual-frequency observations with the newest smartphones can therefore help to reduce or model these error sources leading to higher positioning accuracies with higher reliability. The following section describes two positioning methods, i.e., PPP and DGNSS, and how they help reducing errors caused by the atmosphere and by multipath effects can be reduced, i.e. PPP and DGNSS.

2.4. Precise Point Positioning (PPP)

PPP is a method for reducing atmospheric error influences and for more accurate positioning. As with SPP, this is an absolute positioning method. In contrast to SPP, however, this is much more accurate, since the position determination is based on phase measurements of the carrier frequencies, e.g. from GPS L1 and L5 observations of the smartpohone. The code observations serve only to determine an approximate solution, which is necessary, since the phase measurement is ambiguous in contrast to the code measurement. The phase ambiguity is an unknown integer, which describes the number of whole wave cycles between the satellite and the receiver before phase synchronization is achieved in the receiver. If the carrier phase is detected, it is followed up until a signal interruption or phase jump, i.e., a so-called cycle slip, occurs. After each cycle slip the ambiguity must be solved anew. The solution requires a certain convergence period, during which there must be no signal interruption. It is therefore of crucial importance that the observations are as uninterrupted as possible (Heßelbarth, 2011; Reußner, 2016).

With PPP, accuracy in the centimetre range can be achieved. The broadcast ephemeris are not sufficient for this purpose. More precise satellite orbit data and satellite clock corrections are needed. These are provided by the International GNSS Service (IGS) on different accuracy levels, i.e, rapid and ultra-rapid orbits for real-time applications and final orbits for post-processing (Reußner, 2016). Thus, in this work the final orbits from IGS are used for the calculation of the PPP solutions.

As described above, the ionosphere is responsible for most of the atmospheric error influences. In order to reduce this influence, the properties of the medium can be exploited, since the propagation velocity of electromagnetic waves in the ionosphere is frequency-dependent. As aforementioned, GNSS systems transmit their signals via more than one carrier frequency. Table 2 shows the carrier frequencies of the four systems studied in this paper. At least two carrier phases are observed during Precise Point Positioning. The difference in time between the two signals allows conclusions to be drawn about the electron content of the atmosphere and the measurements can be corrected (Reußner, 2016).

GPS		GLONASS		GALILEO		BEIDOU	
L1	*1575.42 MHz*	R1	*1598 - 1605 MHz*	E1	*1575.42 MHz*	B1	*1561.10 MHz*
L2	*1227.60 MHz*	R2	*1243 - 1249 MHz*	E5a	*1176.45 MHz*	B2	*1207.14 MHz*
L5	*1176.45 MHz*	R3	*1202.025 MHz*	E5b	*1207.14 MHz*	B3	*1268.52 MHz*
				E6	*1278.75 MHz*		

Table 2. Overview of the carrier frequencies of the used GNSS.

2.5. Differential GNSS (DGNSS)

Another method for increasing accuracy is DGNSS. As with PPP, the position determination is based on both phase and code observations. Unlike SPP and PPP, this is a relative method, since the position is determined in relation to a reference station with known coordinates. This procedure therefore requires at least two GNSS receivers. One is operated as a rover, the other as a base (reference) station. While the base receiver is stationary, the rover is a mobile GNSS receiver. The position of the rover is unknown and needs to be determined. As described in section 2.3, a travel time delay occurs along the signal path due to atmospheric conditions. If rover and base station are close to each other, the atmospheric influences can be assumed to be similar for both receivers. Measurements shall be carried out with both receivers, which shall cover the same measurement period. In addition to the already known coordinates of the base, one obtains a position determined by GNSS for the rover. From the difference between the measured position and the known coordinates of the base station, conclusions can be drawn about the properties of the atmosphere and correction data can be determined. These correction data can be applied to the measured values of the rover. Thus, accuracy is increased. Since the atmospheric influences are local, this method becomes less precise as the two receptors are further apart. The line or vector between rover and base is called baseline or base vector, respectively (Heßelbarth, 2011; Reußner, 2016).

The correction of the measurement signals can be done either in post-processing or in real-time (so-called Real-Time Kinematic, RTK) during the measurement. In RTK, the correction data must be transmitted to the rover in real-time via a data link. This is usually done via the existing mobile network. In practice, it is often not necessary to set up an own reference station, since it is often possible to use an existing reference station network, so-called Continuously Operating Reference Station (CORS) networks. In Austria, such a network is operated by Energie Burgenland AG, ÖBB Infrastruktur AG and Wiener Netze GmbH. The station network, called EPOSA (Echtzeit Positionierung Austria), consists of 40 reference stations, which are distributed throughout Austria. The service provides both real-time data and RINEX data for post-processing. With the Austrian Positioning Service (APOS), the Federal Office of Surveying and Mapping (BEV) is providing another service with a similar function and its own reference stations. EPOSA is used in this work (EPOSA, 2021).

If there is no reference station at an acceptable distance near the measuring area, it is possible to calculate a Virtual Reference Station (VRS) by interpolation from the surrounding reference stations (EPOSA, 2021).

Results of DGNSS solutions for the conducted long-term observations with the Google Pixel 5 are not presented here in the following. They can be found in Retscher and Weigert (2021). Here the focus is led more on measurements with shorter observation periods of several minutes and down to seconds in gthe case of observations in the stop-and-go and kinematic mode.

2.6. Coordinate Systems and Transformations

To determine the satellite-ephemeris, a globally uniform reference system is needed. This is provided by the WGS84 in the case of GPS, which is based on the International Terrestrial Reference System (ITRS). If a position is determined using GNSS, coordinates are obtained in WGS84, since the determined position refers to the position of the satellites. In many cases, it is necessary to transform the coordinates into a regional system. The European Terrestrial Reference System 1989 (ETRS89) is used in large parts of Europe because it represents a uniform and stable system for the Eurasian Plate. The ETRS89 was aligned with the ITRS in 1989. Since then, due to the continental drift, the Eurasian Plate has moved about 2.5 cm to the Northeast every year. The current positional deviation of the two systems is in the order of a few decimeters. The actual value is position dependent due to the additional rotation of the Eurasian plate. The ETRS89 is realized in Austria by the Austrian Positioning Service (APOS) (Höggerl et al, 2007; Killet, 2010).

3. Analyses of Static and Kinematic Observations

For the analyses, static long-term observations were carried out first (Retscher and Weigert, 2021). In these measurements, the smartphone was mounted on a measuring pillar with a holder in a tripod (see Figure 2 on the left). Moreover, measurements with static short observation periods of around 20 minutes were carried out. These measurement campaigns were followed by several tests along different trajectories which were observed either in stop-and-go or kinematic mode. In the following, the satellite availability and quality is briefly reviewed and then the main findings of the static long- and short-term observations and a detailed analysis of the kinematic observations are presented.

3.1. Satellite Availability and Quality of the Static Long-term Observations

The Google Pixel 5 was able to observe GNSS signals from a total of 56 satellites over the whole observation period of 150 minutes in the static long-term observations. Of these, however, only 21 satellites were recorded on both frequency bands L1 and L5. Thereby the number of satellites observed was highest for GPS, but only about half could be observed on two frequencies. This is expected as only half of all available GNSS satellites in space broadcast L5 signals at the time of the experiments. In contrast, the number of Galileo satellites was smaller, but almost all satellites were able to receive both frequencies. Figures 3 and 4 show the satellite constellation of the GPS and Galileo satellites for the GPS frequency bands L1 (left) and L5 (right) and the Galileo E1 (left) and E5a (right), respectively, in the form of skyplots. In these plots the satellite motion, signal strength and the number of signal interruptions can be seen clearly. The signal strength is described on the basis of a colour scale, signal interruptions caused by cycle slips are marked by a red bar. Eight GPS satellites could be observed on only one frequency (see Figure 3). Many of these satellites are located more in the West. It is obvious that some of the satellites, from which only the L1 band could be observed, have a higher signal strength. The high number of cycle slips in the Pixel 5 observations is clearly visible. From the skyplots of the Galileo satellites in the frequency Galileo bands E1 and E5a presented in Figure 4 can be seen that all satellites could be observed on two frequency bands. Similar as for the GPS observations, cycle slips occur more frequently in the E5a band than in the E1 band. Overall, the signal quality of the Pixel 5 receiver is significantly lower compared to a professional geodetic GNSS receiver. The signals are considerably weaker and there are more frequent signal outages. In Retscher and Weigert (2021) the observations of the Pixel 5 with the nearby geodetic reference receiver SP80 placed on a second measuring pillar in a distance of only 12 m on the roof of the EI building (see Figure 2) are compared. With the SP80, signal outages occur only at a very low elevation. While the signal strength of the reference receiver is highest at the zenith, the Pixel 5 still shows signal interruptions. Only in the West were relatively continuous signals with an SNR (Signal to Noise Ratio) of more than 45 dBHz.

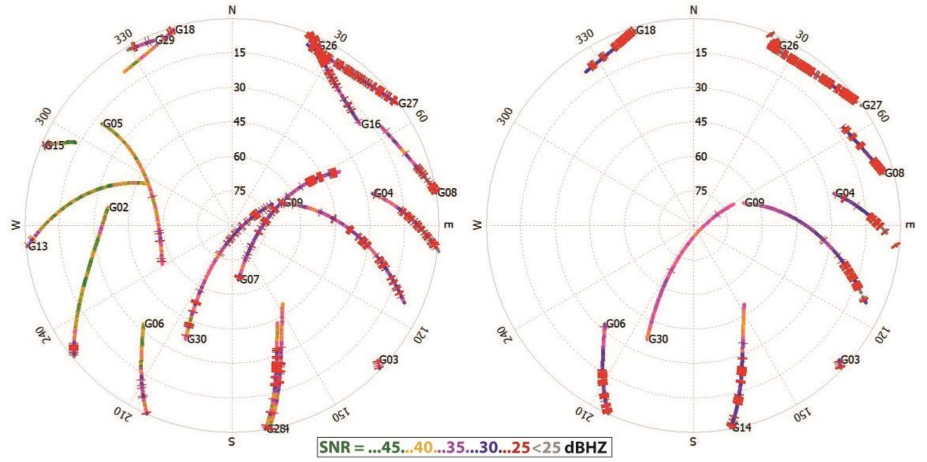

Figure 3. Skyplots showing the tracked GPS satellites of the Google Pixel 5 on L1 (left) and L5 (right) with coloured visualisation of the Signal to Noise Ration (SNR).

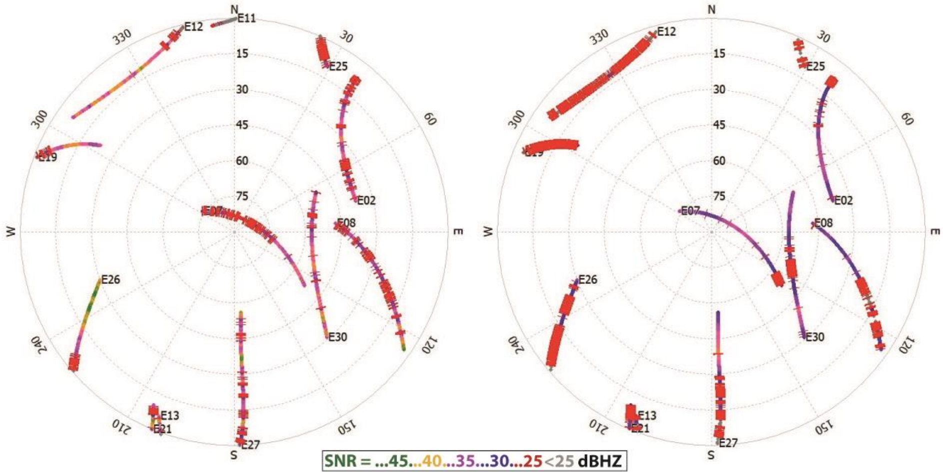

Figure 4. Skyplots showing the tracked Galileo satellites of the Google Pixel 5 on E1 (left) and E5a (right) with coloured visualisation of the Signal to Noise Ration (SNR).

3.2. Results of Short Static Observation Periods

Further measurements were carried out at Karlsplatz where a control point network including several reference points is available. These measurements represent typical real world measurement scenarios, such as GIS data acquisition, such as tree cadastre, lantern cadastre, etc. The Pixel 5 is mounted on a tripod and placed on known points (see Figure 2 on the right). Three surveys are carried out, each with 20 minutes of observation time. Different obstructions of the satellite signals are prevailing on the three chosen reference points N07, N08 and N09 of the control point network. While the points N09 and N08 are relatively in open space, N07 is located between several broad-leaved trees. Since the measurements have been carried out in winter, the trees do not bear any foliage. In the following, the calculated SPP and PPP solutions are presented and analysed.

3.2.1 SPP Solutions

For the three reference points N07, N08 and N09, SPP solutions for the individual systems and a multi-GNSS solution are calculated. In the multi-GNSS solution, the individual systems are combined with Matlab. This is done for the entire observation period of 20 minutes. Table 3 shows the solutions for position N07, Table 4 for N08 and Table 4 for N09.

SPP	20 Min	17.12.2020 11:10 - 11:30			N07						
	n	Std E	Std N	Std U	Std 2D	Std 3D	Dev E	Dev N	Dev U	Dev 2D	Dev 3D
GPS	539	17.235	32.911	48.135	37.151	60.804	4.450	18.117	-16.983	18.655	25.228
GLONASS	369	40.812	53.238	46.900	67.082	81.851	-0.957	16.274	-30.079	16.302	34.212
GALILEO	534	10.999	12.478	28.7971	16.634	33.256	-2.992	-3.392	-10.669	4.523	11.588
BEIDOU	480	12.002	8.954	31.268	14.974	34.668	5.832	-0.032	9.885	5.832	11.477
Multi GNSS	1922	16.862	21.407	38.651	27.250	47.292	1.337	4.161	-9.739	4.371	10.675

Table 3. Comparison of the SPP solutions over a 20-minute observation period for the reference point N07.

SPP	20 Min	17.12.2020 10:46 - 11:06			N08						
	n	Std E	Std N	Std U	Std 2D	Std 3D	Dev E	Dev N	Dev U	Dev 2D	Dev 3D
GPS	270	9.248	23.738	28.934	25.476	38.551	-0.217	0.288	-21.455	0.361	21.458
GLONASS	837	11.863	18.469	20.655	21.951	30.141	-9.349	4.618	-16.314	10.427	19.362
GALILEO	915	2.909	6.661	10.3231	7.268	12.625	-0.474	0.263	-11.376	0.542	11.389
BEIDOU	554	8.535	2.329	16.608	8.847	18.818	2.353	6.511	9.703	6.924	11.919
Multi GNSS	2576	7.427	9.129	17.754	11.768	21.300	-2.108	2.709	-9.441	3.433	10.045

Table 4. Comparison of the SPP solutions over a 20-minute observation period for the reference point N08.

SPP	20 Min	17.12.2020 10:20 - 10:40			N09						
	n	Std E	Std N	Std U	Std 2D	Std 3D	Dev E	Dev N	Dev U	Dev 2D	Dev 3D
GPS	393	10.129	11.289	12.889	15.167	19.904	-3.714	3.512	-12.201	5.112	13.229
GLONASS	640	16.821	17.708	39.453	24.424	46.401	-6.824	4.670	-14.565	8.268	16.748
GALILEO	276	12.318	38.452	31.6746	40.376	51.318	-7.085	-19.078	-45.453	20.351	49.801
BEIDOU	342	5.165	7.840	17.423	9.389	19.792	2.185	-8.563	-37.729	8.837	38.750
Multi GNSS	1651	11.915	14.093	26.506	18.455	32.297	-3.977	-0.830	-24.258	4.063	24.596

Table 5. Comparison of the SPP solutions over a 20-minute observation period for the reference point N09.

The number of calculated positions n varies greatly depending on the system used. The location also influences the measurement result. For reference point N07 the highest number of solutions (539) can be determined using GPS compared to the other points. For point N08, on the other hand, the lowest number (270) is determined with GPS. The number of solutions of the other systems also varies significantly depending on the point of view. Beidou delivers the most constant number of solutions. This varies only by 212 solutions between positions N07 and N09. Standard deviations are also subject to strong fluctuations and vary depending on the system and the point location. The smallest 2D standard deviation (i.e., Std 2D in the Tables) of around 7.3 m is achieved at position N07 with Galileo. The largest positional standard deviation of around 67.1 m is again at point N07 with Glonass. These GNSS and points also achieve the lowest (12.6 m) and largest (81.9 m) 3D standard deviations. In the following, the deviations from the known coordinates of the reference points are analysed. The results of Helmert's point position error (i.e., Dev 2D) differ by a few meters depending on the system and the point of view. The lowest deviation is achieved with GPS at point N08. It is only 0.36 m and is at the same time the solution for which the fewest individual solutions have been identified. The GPS solution for which the most solutions are available (N07, n=539) achieves an inaccurate result with a deviation of more than 18 m. This means most likely that more outliers in the data have influenced the result significantly. With more than 20 m, only the GLONASS solution for position N09 is less accurate. When the height component is included in the deviation, the best results are achieved with the multi-GNSS solutions. For points N08 and N07 these are just over 10 m, for point N09 a deviation of 24.6 m is achieved. Overall, the multi-GNSS solution achieves position deviations of about 4 m on all points.

3.2.2 PPP Solutions

In the following, PPP solutions are calculated for the three reference points. As in the case of long-term measurement, no solutions can be estimated for Galileo and Beidou because of their low signal quality. For GPS, two carrier frequencies can be included in the calculation. For Glonass, only the frequency R1 is available. Broadcast ephemeris are used. Figure 5 shows plots of the determined numbers of solutions for point N09 (left) and N07 (right). The distribution of the solutions for position N08 is similar to that for position N09 and is therefore not shown here. The GPS solutions are shown in green and the Glonass solutions in blue. If PPP solutions cannot be determined, the employed software package RTKPost automatically calculates SPP solutions. These are represented in red in the Figure. There is a distance of several meters between the GPS and GLONASS solutions at N09. At N07 this distance is even larger. Observations from point N07 have a lower quality and many SPP solutions are estimated only. Similar as for the SPP solutions in section 3.2.1, Tables 6, 7 and 8 summarise the PPP results for each reference point. In addition to the number of identified solutions per system, the quality (Q) of the solutions is also given in percent. Q describes the proportion of PPP solutions. The remaining solutions are SPP solutions.

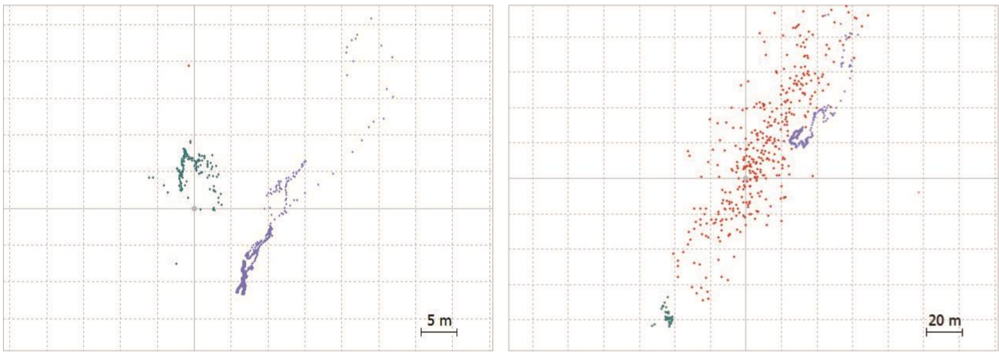

Figure 5. Comparison of PPP solutions for GPS (turquoise) and GLONASS (purple); on the left is point N09, on the right N07. Solutions for which only one SPP solution could be determined are shown in red. Note, the different scale of the grids.

PPP	20 Min		17.12.2020 11:10-11:30		N07							
	n	Q [%]	Std E	Std N	Std U	Std 2D	Std 3D	Dev E	Dev N	Dev U	Dev 2D	Dev 3D
GPS	380	17.6	21.585	40.022	65.366	45.472	79.627	9.174	25.459	-19.463	27.062	33.333
GLONASS	340	99.8	3.993	3.895	4.806	5.578	7.363	-20.501	0.810	-34.893	20.517	40.478
Multi GNSS	720	56.4	16.829	21.529	29.141	27.326	39.949	-8.518	8.700	-22.311	12.176	25.417

Table 6. Comparison of the PPP solutions for GPS and GLONASS over a 20-minute observation period at point N07.

PPP	20 Min		17.12.2020 10:46-11:06		N08							
	n	Q [%]	Std E	Std N	Std U	Std 2D	Std 3D	Dev E	Dev N	Dev U	Dev 2D	Dev 3D
GPS	189	84.4	1.596	4.636	9.613	4.903	10.791	-1.046	-11.199	-27.989	11.247	30.164
GLONASS	797	100.0	0.839	2.018	2.059	2.185	3.003	-8.731	2.052	-13.874	8.969	16.521
Multi GNSS	988	95.6	2.024	5.097	4.762	5.484	7.263	-8.017	-0.169	-15.723	8.018	17.650

Table 7. Comparison of the PPP solutions for GPS and GLONASS over a 20-minute observation period at point N08.

PPP	20 Min		17.12.2020 10:20-10:40		N09							
	n	Q [%]	Std E	Std N	Std U	Std 2D	Std 3D	Dev E	Dev N	Dev U	Dev 2D	Dev 3D
GPS	245	99.0	1.090	2.581	1.753	2.802	3.305	-1.097	-4.159	-12.044	4.301	12.789
GLONASS	556	100.0	2.289	2.414	2.770	3.326	4.328	-5.251	6.537	-17.473	8.385	19.380
Multi GNSS	799	99.9	2.582	4.404	3.065	5.105	5.955	-3.898	3.641	-15.642	5.334	16.527

Table 8. Comparison of the PPP solutions for GPS and GLONASS over a 20-minute observation period at point N09.

At the reference points N07 and N08 much more solutions are achieved with Glonass than with GPS. Especially at N07, where Q is only 17.6% for the GPS results. Overall, Glonass solutions are of a higher quality than GPS solutions. With Glonass, 100% PPP solutions can usually be calculated, even on point N07. Using GPS this result is not achievable. The quality of the solutions has a major influence on the standard deviations. The solution with the lowest quality (GPS; N07; 17.6%) also has the largest standard deviation (in 2D 45.5 m; and in 3D 79.6 m). The smallest standard deviation is achieved with Glonass for point N08. This is about 2 m in 2D and about 3 m in 3D. The total deviations from ground truth are similar. The results with a low quality have a large deviation. This reaches for the reference points more than 27 m. The best result can be achieved with the GPS solution for position N09. The deviations are about 4 m in 2D and 12.9 m in 3D. The multi-GNSS solutions vary by several meters depending on the reference point. For the position, results for the standard deviations are obtained between 4 and 13 m, the total deviation from the known reference point coordinates is between 16 and 26 m.

Compared to long-term observations, the 20 minute observations are much more imprecise. Thus, if the requirements in terms of positioning accuracies are high, longer observation times are needed with PPP.

3.3. Measurements along a Straight Trajectory

For application scenarios such as line documentation, e.g. for underground power lines, or the approximate recording of trajectories, measurements are carried out along a straight line with a total length of 95.86 m on Karlsplatz. The measurement scenario is such that a user walks at a slow pace with the smartphone in his hand along a predefined line both ways in the outward and in the return direction between the two known reference points N07 and N09. Every five meters a short stop with a duration of several seconds is made. Thus, the measurements can be seen as pseudo-kinematic or in stop-and-go mode.

With RTKPost the GPS, Glonass, Galileo and Beidou solutions for the outward and return journey were calculated. The resulting 8 position files are transformed, merged and plotted with Matlab (Figure 6). A total of 3,497 positioning solutions are available. The resulting point cloud is widely scattered. The course and direction of the track can be roughly estimated in the form of a cluster. There are many faraway outliers and it is not possible to make precise statements about the path taken. Consequently, the results need to be further processed. For this purpose, an adjusted straight line is laid through the point cloud. This can then be compared with the calculated distance between the two known reference points. With Matlab, a neighbourhood analysis is performed to eliminate outliers and more distant points. For each point, the number of neighbours within a defined radius is determined. If the number falls below a predefined limit, the point is not included in the calculation. The radius and the limit are determined by experimentation. The adjusted line should be optimally adapted to the known straight path. The best result was achieved with a radius of 5 m and a minimum number of 30 neighbours (Figure 7). A total of 1,491 points are eliminated (blue) and 2006 points are included in the compensation (red).

The adjusted line is shown in red and the ground truth in green in Figure 7. The actual distance can be easily reproduced by the straight line. The estimated adjusted line, however, has a slightly lower slope. This results in an increasing distance between the two straight lines. The maximum distance obtained resulted in 0.97 m. A problem is the start and end point of the determined trajectory. The adjusted line is too long and extends more than 10 m beyond the distance between the known points serving as ground truth (Retscher and Weigert, 2021).

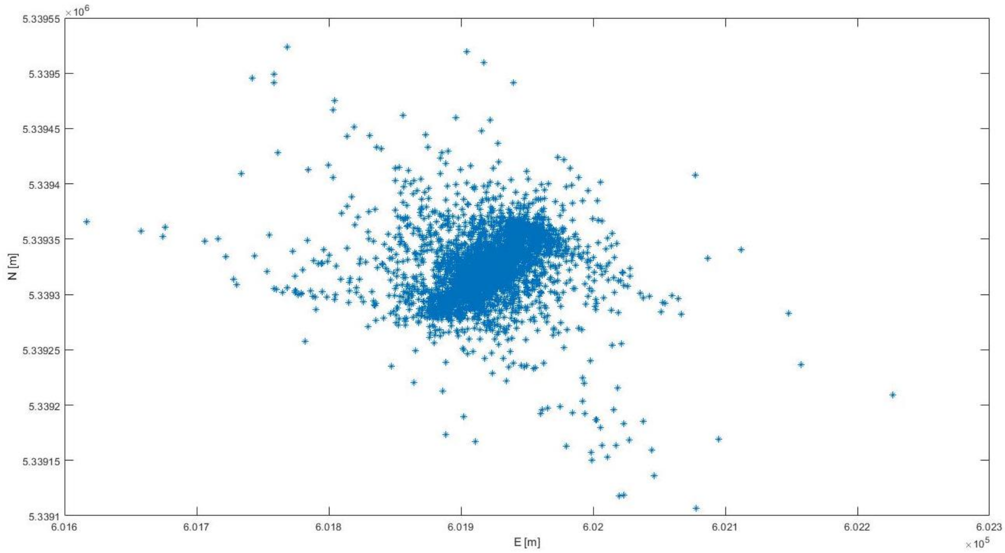

Figure 6. Point cloud with SPP solutions along the route to be investigated. The point cloud includes solutions for the round trip, as well as for all four GNSS.

In addition to the SPP solutions, the PPP solutions are estimated. As with previous measurements, PPP solutions can only be calculated for GPS and Glonass. A total of 1,142 individual solutions of the two systems are available for the round trip. This data is processed with Matlab similar as with the SPP solution. The unprocessed point cloud of the solutions gave similar results as the SPP solutions shown in Figure 8. There are fewer points in total than in the SPP solution. The point density along the reference line is lower and there are many outliers. Despite the variation of the radius and the boundary during the neighbourhood analysis, a good adaptation to the actual distance is not achieved. The deviations of the two lines are many meters apart. The main reason for the lower accuracies is here that only GPS and Glonass can be used instead of all four GNSS as in the SPP solutions.

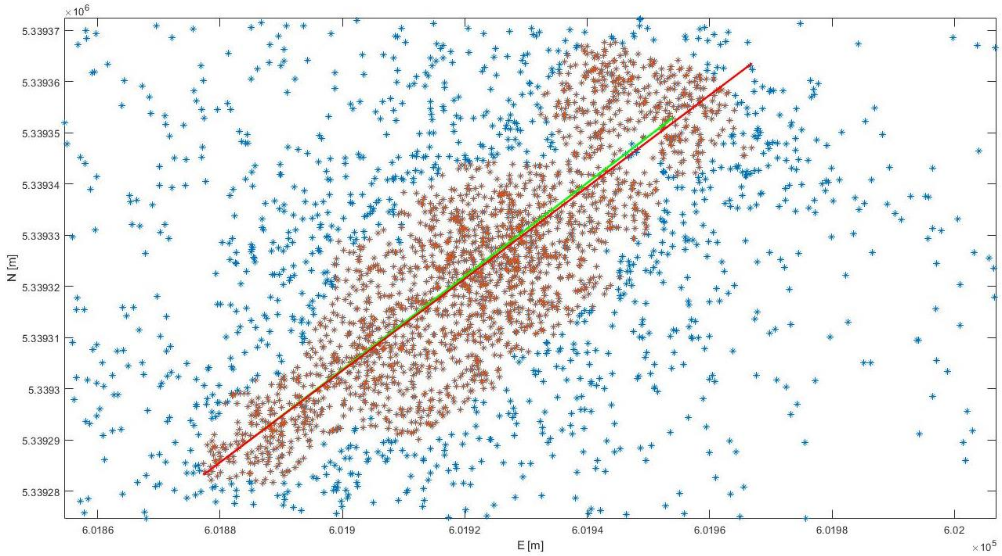

Figure 7. Adjusted line of the point cloud along the straight route. The distance calculated from the known coordinates is shown in green. The distance calculated with the help of the neighbourhood analysis from the points is shown in red. The red points have been included in the calculation of the adjusted line (Source: Retscher and Weigert (2021)).

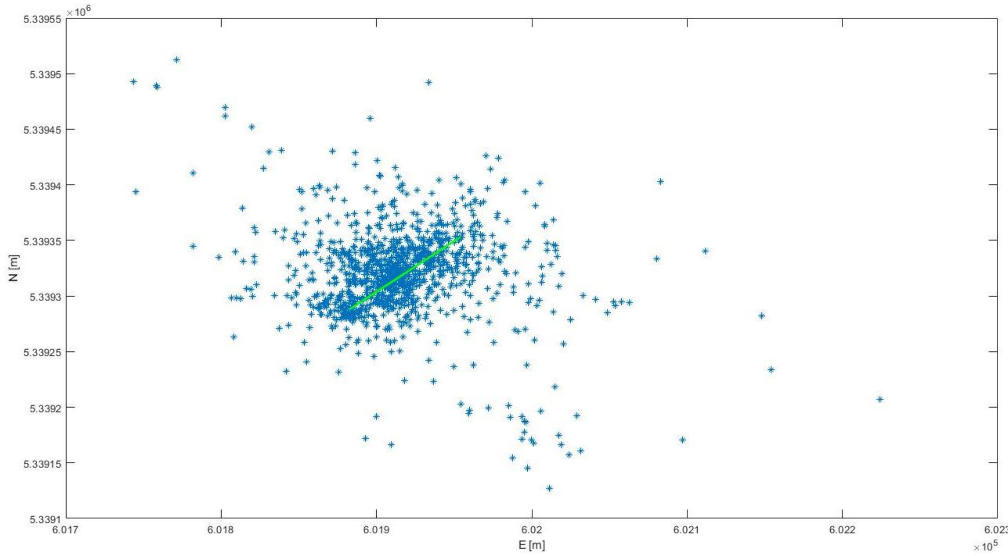

Figure 8. Point cloud with PPP solutions along the route to be investigated. The point cloud includes GPS and Glonass solutions for the round trip. In addition, the reference trajectory is shown as straight line.

4. Summary of the Main Results and Conclusions

Various experiments were carried out in this study, such as long-term measuremenst of 150 minutes, several practical measurements over an observation period of 20 minutes as well as stop-and-go and kinematic measurements. In this paper, short-term static observations and a straight trajectory measured in stop-and-go mode is analyzed. The measurement data were evaluated using the positioning methods SPP and PPP. The main findings and results are summarized in the following, with reference to the criteria investigated, i.e., measurement effort and costs, quality, accuracy and repeatability of the measurements.

4.1. Measurement Effort and Costs

The effort for the measurements is quite low. For equipment, only a mounting device for the mobile phone and a tripod are required for long-term observations on reference points depending on the measurement task. Especially if PPP is chosen as positioning method, longer observation times should be chosen, as the quality of the measurement data varies considerably over time. Here the smartphone must be placed reliably stationary. The analysis of the data is more complex. Only observation files can be created with the Geo++ RINEX Logger. The satellite ephemeris must be obtained elsewhere, such as from EPOSA for broadcast ephemeris and from IGS for precise final orbits. The position determination was performed with the freely available RTKLib software package. The calculated solution point clouds were then transformed with Matlab to UTM and further processed into a single positional solution

4.2. Signal Quality

Compared to geodetic GNSS receivers, the quality of the observations is significantly lower. The recorded satellite signals are weaker and there are frequent signal outages, which also occur for observations in the zenith. Obvious from the tests is that the satellites with strong L1 signals from GPS could not always be observed on the second frequency L5. Most of the Galileo satellites could be received on both frequencies, however, the signals of the bands L5 and E5a are weaker overall than the signals of the bands L1 and E1. The high number of signal outages and the often low signal strength indicated by the SNR make further evaluation difficult. PPP solutions can only be calculated for GPS and Glonass. However, this is often not possible for the entire observation period. At these points, RTKLib automatically switches to SPP mode. The fact that a dual-frequency receiver is installed in the Pixel 5 can therefore only be used to a limited extent in our experiments.

4.3. Achievable Positioning Accuracies

As expected, SPP solutions have significantly higher standard deviations than PPP. They resulted on the few meter level. For PPP, they are often less than one metre. The standard deviations of the Glonass solutions are significantly larger than the ones of GPS. If one considers the deviations from the ground truth from the coordinates of the reference points, the results could not be generalized as significant differences in achievable accuracies occurred for the individual methods. Clear differences of the results can only be seen for GPS in the long-term measurement. Both Galileo and Beidou provide SPP results with higher positioning accuracy for long-term measurements. However, these cannot be compared with the other solutions, as no PPP processing is possible for Galileo or Beidou. If the different GNSS are combined, SPP can achieve results with a deviation of less than half a meter in dependence of the chosen observation time period. The combined solution of all four systems is not always the best, however, as it is strongly influenced by the very inaccurate Glonass results. However, position deviations of less than 30 cm could be achieved with different GNSS combinations (see also Retscher and Weigert, 2021).

For the observations over 20 minutes the differences between the results are in the range of several meters for both methods SPP and PPP. The results vary significantly between the different GNSS combinations and the chosen reference points. Because of the high variation, it is difficult to say which system and method can be used to obtain the more accurate results. The SPP multi-GNSS solution, consisting of all four systems, can guarantee a positional deviation of less than 5 m for all three reference points on Karlsplatz. The PPP dual-GNSS solutions, consisting of GPS and GLONASS, provide a positional deviation of similar quality depending mainly on the length of the observation period.

SPP and PPP solutions were also calculated for the measurement along the chosen trajectory. From the point cloud of the SPP solutions, an adjusted straight line could be estimated, which represents the true trajectory well. The maximum deviation of the measured and true distance is less than one meter. However, the adjusted line resulted in a longer distance than the true distance of few meters which causes that the start and end point cannot be estimated precisely from the measurements.

4.4. Repeatability

In the paper of Retscher and Weigert (2021), the long-term observation for GPS were also divided into measuring intervals of 10 minutes each and position solutions were calculated using the methods SPP and PPP, using both broadcast ephemeris and final orbits from IGS for the PPP calculation. The standard deviations for these solutions remain largely constant in the intervals. However, the accuracy varies significantly regardless of the method used. The measurement results therefore show poor repeatability for the short observation periods of 10 minutes. A major dependence on the prevailing satellite constellation in these 10-minute periods is seen. Further analyses are required for different length of observation periods.

4.5. Final Outcome Discussion

Observations on two frequency bands can only be made currently for GPS and Galileo with the Google Pixel 5. In this case, however, the observation data of the second frequency band L5 was of lower quality in the conducted experiments, so that unfortunately evaluation of both frequency bands is only possible to a limited extent. Due to the high number of signal outages, a position determination based on phase observations was not possible for all satellite systems. In most cases they could only be made for GPS. The results depend also on the chosen ephemeris data. If IGS final orbits are also used for PPP, the accuracy is significantly higher.

Whether the Google Pixel 5 or a similar smartphone is currently suitable for solving measurement tasks in surveying depends essentially on the requirements of the application. If accuracies of less than half a meter are sufficient smartphones can replace PDAs or receivers for GIS data acquisition. However, if short observation times are required, the deviations often amount to several meters. The in the literature reported cm-accuracies for the PPP with comparable smartphone models could not be confirmed from the experiments. These are mostly based on extensive calibrations for the smartphone GNSS antennae to determine the phase center variations, see e.g. in Darugna (2021) and Wanninger and Heßelbarth (2020), and are therefore not always for practical usage in GIS and LBS applications.

4.6. Outlook on Future Research Questions

For the future work, we will concentrate on the following research questions:

- Which results can be achieved for different observation time periods with PPP?
- How do the other GNSS and the SPP multi-GNSS solutions behave during the measurement?
- How do the L5 observations look like for different satellite constellations?
- How long is the convergence period of PPP solutions as a function of the observation time?
- Which positioning accuracies can be achieved in real-time?

- Which positioning accuracy is achieved in real-time positioning with the CORS RTK services?
- Do similar problems occur with comparable smartphones?
- Are the accuracies to be achieved comparable for different smartphones?
- Does the App used for data acquisition have an impact on the results?

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