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Abstract: The possibility to manage pseudorange and carrier-phase measurements from the Global Navigation Satellite System (GNSS) chipset installed on smartphones and tablets with an Android operating system has changed the concept of precise positioning with portable devices. The goal of this work is to compare the positioning performances obtained with a smartphone and an external mass-market GNSS receiver both in real-time and post-processing. The attention is also focused not only on the accuracy and precision, but also on the possibility to determine the phase ambiguity values as integer (fixed positioning) that it is still a challenging aspect for mass-market devices: if the mass-market receiver provides good results under all points of view both for real-time and post-processing solutions (with precisions and accuracies of about 5 cm and 1 cm, respectively), the smartphone has a bad behaviour (order of magnitude of some meters) due to the noise of its measurements.

1 INTRODUCTION

Nowadays, smartphone technology is widespread almost all people have one, not only used for call others but also to guide them to some places and share their locations in this context navigation systems have become important part of everyday life.

GNSS based systems do not work in locations where no GNSS signals can be received or in very noisy environments, as in urban canyons (Masiero et al., 2014): in all other places GNSS equipment can offer an interesting solution for positioning, navigation purposes or location in many places, such as at university, in shopping malls, at train stations or in large buildings (Federici et al., 2013).

In order to devise a successful outdoor navigation solution, it is important to understand the quality and accuracy of smartphones' integrated sensors (Zandbergen and Barbeau, 2011) while using smartphone can provide good accuracy using assisted GNSS (A-GNSS) systems, which can obtain the required data from other GNSS permanent stations or from internet connected server (Van Diggelen, 2009). In both cases, it is mandatory to have the access to GNSS raw measurements, as pseudoranges and carrier-phase.

Until 2016 was not possible to have GNSS raw data by mobile platform likewise high level API such as iOS and Android which not allowed to access raw data, but it was only possible to get raw measurements from GNSS receivers dedicated only for precise positioning (also single frequency).

However, with the release of Android Nougat operating system (version 7.x or 8.x) some smart devices allow the direct access to raw data and PVT solution by acquiring pseudoranges and carrier-phase from the chipset inside (Humphreys et al., 2016; Zhang et al., 2018). Many other sensors are available today on smartphones: most of them are related to internal applications (e.g., proximity sensor, light sensors) while others (e.g., inertial measurements unit and camera) can be used for estimating a positioning solution, but these aspects are out of the scope of this paper.

Many studies are already done about positioning solutions (Lachapelle et al., 2018; Zhang et al., 2018), considering GPS/GNSS chipset and a European task force have been activated in last years (https://www.gsa.europa.eu/gnss-raw-measurements-task-force).

However, this paper presents the performances of one smartphone (Huawei P10+) with Android operating system compared to those obtainable with another mass-market GNSS receiver (u-blox NEO M8T), with the same characteristics of the smartphone's one, equipped with a patch antenna.

Many tests have been conducted in outdoor, considering static and kinematic positioning, in different conditions in terms of multipath effects and

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number of visible satellites, using different software for obtaining a post-processed positioning solutions. After this introduction, a section related to the GNSS positioning techniques available with smartphone technology is provided. Then, the test cases and the obtained results will be shown before some comments and conclusions.

2 GNSS POSITIONING TECHNIQUE WITH SMARTPHONE

Only measuring the distances (pseudoranges) between the user's receiver and the position of at least four satellites of the same constellation it is possible to obtain a GNSS solution (Kaplan and Hegarty, 2005; Misra and Enge, 2006). The distance between receiver and satellite is proportional to the signal propagation time, if the transmitter and receiver clock are perfectly synchronized. Of course, this does not happen so the satellites' and receivers' clock biases have to be estimated. In addition, other effects affect the GNSS signals such as thermal noise, uncompensated biases, multipath, and other propagation effects. But the biggest error source is given by the atmospheric propagation effects, in particular the ionospheric and tropospheric delays and ionospheric scintillations. If these biases are not estimated or removed, the positioning error can be greater than 30 m, making the GNSS positioning useless for most of applications. As widely described in literature, two main approaches can be adopted: the post-processing or real-time techniques. This last kind of method can be used if the accuracy required is less than 5 cm (Dabove and Manzino, 2014), a condition that is not generally requested and obtainable if smart devices are considered (Fissore et al., 2018; Dabove and Di Pietra, 2019).

The post-processing approach is generally followed when a high level of accuracy is required or when it is not possible to estimate some biases in real time in an accurate way, exploiting for example the use of two or more frequencies. This generally happens considering the typical receivers used for positioning purposes, such as geodetic or GIS (Hoffmann-Wellenhof et al., 2008). Starting from last decade, with the advent of mass-market receivers, GNSS positioning has become more common because the cost of GNSS receivers and antennas have been decreased up to few US dollars.

Most of GNSS receivers available inside smartphones are not multi-frequency (Robustelli et al., 2019) but only single-frequency receivers, so only measurements referred to the L1 frequency (L1 band) can be exploited. In that case, it is not possible to apply the most common differencing methods, also known as double or triple differences (Hoffmann-Wellenhof et al., 2008 ; Dabove et al., 2014), nor to combine different observations (Cina et al. 2014). Therefore, the only two possible solutions are the single difference approach (considering one receiver and a reference satellite) or modeling the GNSS biases (e.g. iono and tropospheric delays, satellite and receiver clock drifts) using mathematical models.

3 TEST SETUP

Many tests were done both in static and kinematic conditions. The smartphone considered in these tests is the Huawei P10+ which characteristics are summarized in Table 1 with those of the u-blox NEO M8T GNSS receiver, used as comparison.

Table 1: The instruments used in these tests.

Receiver	Huawei P10+	u-blox NEO M8T
Image		
Constellation	GPS	GPS + GLONASS + BeiDou
Observations	C/A, L1, SNR	C/A, L1, SNR
Cost	€ 300	€ 70
Weight [g]	145	8.1
Dimension [mm]	145.3 x 69.3 x 7	40 x 18 x 8

Two different test sites have been investigated, considering different environmental conditions: the first test-site is the roof of the building's office at Politecnico di Torino, an area where the noise and multipath effects are very high and the satellite visibility is reduced due to the presence of other buildings.

Figure 1: The two test sites: the place that represent the noisy environment (left, site A) and an undisturbed place (right, site C).

The second one is an undisturbed site, characterized by the absence of reflective surfaces, electromagnetic disturbances and with optimal conditions for tracking satellites (e.g. no obstructions). These two sites, namely A and C (Figure 1), respectively, represent the two main conditions where a user works or tries to perform positioning activities.

The u-blox receiver needs a software installed in an external device for providing both the raw-measurements and the real-time results. There are many software available today on the market (e.g., those proposed in Kaselimi et al., 2018) that can exploit the owner binary format (.ubx) for obtaining RINEX files or real-time solutions. In this work, we have used the RTKLIB suite (2.4.3) both for extracting the raw data, for converting them in RINEX (using the RTKCONV tool), and for performing the post-processing (using the RTKPOST tool) and real-time (using the RTKNAVI tool) solutions. This software is particularly interesting because it is an open source program package for standard and precise positioning with GNSS many constellations (GPS, GLONASS, Galileo, BeiDou, QZSS, SBAS) and supports various positioning modes with GNSS for both real-time and post-processing approaches: Single, DGPS/DGNSS, Kinematic, Static, Moving-Baseline, Fixed, PPP-Kinematic, PPP-Static and PPP-Fixed. It is also includes Graphical User Interface (GUI) and Command-line User Interface (CUI) with many library functions, related to Satellite and navigation system functions, stream data input and output functions, standard, real-time and post-processing positioning. This software, as already described in bibliography (Takasu and Yasuda, 2009) is expressly affecting because allows to manage the stream data coming from a network of permanent stations that uses NTRIP authentication. In addition RTKLIB allows to fix the phase ambiguities as integer values, using the modified LAMBDA method (Chang et al., 2005), an interesting technique especially for real-time applications where computational speed is crucial. Indeed, the modified LAMBDA (MLAMBDA) method reduces computational complexity of the “classical” LAMBDA (Teunissen 1995).

The same software is not useful for the smartphone because is not still available as an app. Thus, in this case the GEO++ RINEX app is considered, in order help to get the raw measurements and to store these into a RINEX file.

4 RESULTS

As previously said, different test have been conducted considering both static and kinematic approaches. In this section the main interesting results are shown, considering also the two different software used for the post-processing analysis.

4.1 Positioning Performances Considering Different Environments

Firstly, the behaviour of GNSS internal chipset has been analysed considering a post-processing approach. The permanent station, used as master station, is TORI (Turin): this permanent station, that belongs to the EUREF permanent GNSS network (www.epncb.oma.*be*), is composed by a multi-frequency and multi-constellation receiver and a choke ring antenna and is about 250m far from the test sites.

The smartphone has been positioned in two different test sites previously cited, which coordinates are known. These first analyses are made considering the RTKLIB software and different positioning techniques: single point positioning (SPP), static and kinematic. Moreover, different session length have been considered (10, 30 and 60 mins) in order to verify if there is a correlation between the length of the session and the precision of the solutions. The results are presented in Table 2. All solutions are obtained applying atmospheric corrections: Saastamoinen model was used to mitigate the tropospheric delay using dry and wet components and Klobuchar for the ionospheric one, setting the cut off elevation as 10°. All results are obtained fixing the phase ambiguities according to the “Fix and hold” method (Dabove and Manzino, 2014).

Table 2: Precision of the positioning results using Huawei P10+.

Location	(Min)	Method	E(m)	N(m)	U(m)
A	10	Static	8.991	10.462	10.933
		Kin	23.867	18.414	36.343
		SPP	27.983	20.626	42.507
C	10	Static	0.048	0.142	0.118
		Kin	5.505	4.821	9.373
		SPP	6.418	5.791	11.126
A	30	Static	3.915	6.844	10.131
		Kin	22.475	16.146	56.759
		SPP	33.267	24.791	71.716
C	30	Static	0.864	0.736	1.817
		Kin	12.938	9.756	15.376
		SPP	15.932	12.784	19.766
A	60	Static	35.827	16.135	21.665
		Kin	53.085	33.152	80.066
		SPP	58.724	39.226	88.549
C	60	Static	0.959	0.445	2.071
		Kin	47.321	33.935	39.535
		SPP	50.047	35.247	39.707

After analysing the results in Table 2, it is possible to see how the precision obtained considering the location A is more noisier than those in C, as a result of multipath effects, due to reflective surfaces and a limited satellites visibility. At the same time, it seems that there is no correlation between the session length and the precision, that generally happens if geodetic or GIS receivers are considered: this is due to the quality of the raw measurements, that are more noisier than those obtainable with other mass-market receivers, such as the u-blox one (Dabove and Di Pietra, 2019).

It is important to underline that the kinematic solutions are obtained considering the smartphone settled in the fixed place (as static survey) with the only difference that the solutions are obtained using a dynamic motion in the Kalman filter algorithm. By Analysing these results, it is possible to affirm that this kind of method is not feasible for these instruments, so it is neglected for further analyses.

In order to verify the repeatability of these results, another dataset has been collected in the same places, with the same techniques. Considering the results obtained with RTKLIB (Table 3), it seems that there are no differences with those obtained in the other data collection.

This last dataset has been processed with the LGO 8.3 software, in order to have independent solutions. As shown in Table 4, it is clear that the results are generally slightly better than those obtained with RTKLIB software, even if the behaviour in terms of session length and environmental conditions is the same.

Table 3: Results obtained with RTKLIB software, considering different session lengths and locations.

Method	Location	E(m)	N(m)	U(m)
Static	10min site A	8.991	10.462	10.933
Spp		27.983	20.626	42.507
Static	10min site C	0.048	0.142	0.118
SPP		6.418	5.791	11.126
Static	30 min site A	3.915	6.844	10.131
SPP		33.267	24.791	71.716
Static	30 min site C	0.864	0.736	1.817
SSP		15.932	12.784	19.766
Static	60 min site A	35.827	16.135	21.665
SPP		58.724	39.226	88.549
Static	60 min site C	0.959	0.445	2.071
SPP		50.047	35.247	39.707

Table 4: Results obtained with LGO software, considering different session lengths and locations.

Method	Location	E(m)	N(m)	U(m)
Static	10min site A	1.246	0.955	1.346
SPP		0.782	0.668	0.527
Static	10min site C	0.024	0.016	0.034
SPP		0.492	0.321	0.593
Static	30 min site A	34.991	33.448	81.132
SPP		3.071	1.222	2.81
Static	30 min site C	0.058	0.013	0.044
SSP		0.908	0.443	0.794
Static	60 min site A	156.024	303.553	287.713
SPP		5.425	2.696	4.748
Static	60 min site C	1.246	0.955	1.346
SPP		0.782	0.668	0.527

4.2 Comparison between U-blox and Smartphone Results

In order to compare the results obtained with the smartphone and those with the other low-cost receiver (u-blox), a dedicated test has been performed. Both receivers have been settled on the site C, close to each other, in order to verify the precision in the best possible conditions (good satellite visibility, no obstacles or electromagnetic disturbances).

Table 5: Positioning results using Huawei P10+& u-blox, for a session length of 30 mins.

Device	Method	E (m)	N(m)	U(m)
Huawei	Static	2.910	0.948	16.599
	Kinematic	16.585	12.393	74.289
	SPP	16.646	12.991	74.778
U-blox	Static	0.001	0.001	0.006
	Kinematic	0.618	0.462	1.079
	SPP	3.154	2.003	11.063

Two different measurement campaigns have been considered of 30 mins and 10 mins, respectively. In the last case (Table 6) seems that the smartphone performances are better than those obtainable with u-blox but it is a strange behaviour, that it is not confirmed if the longer session is considered (Table 5). This strange result is due to the noisy of the raw GNSS measurements collected by the smartphone: generally, it is really difficult to be able to filter and de-noise these observations.

Table 6: Positioning results using Huawei P10+& u-blox, for a session length of 10 mins.

Device	Method	E (m)	N(m)	U(m)
Huawei	Static	0.070	0.111	0.507
	Kinematic	7.461	7.287	15.181
	SPP	8.197	6.913	14.763
U-blox	Static	0.140	0.233	0.717
	Kinematic	7.740	9.529	9.424
	SPP	3.016	2.31	6.274

Particularly interesting is the analysis of precision and accuracy obtainable: Table 7, Table 8 and Table 9 show these values for session length of about 1 hour, 30 mins and 10 mins.

Table 7: Accuracy (upper line for each row) and precision (lower line) results.

Device	Method	E (m)	N (m)	U(m)
Huawei	Static	0.16	-0.177	-1.602
		0.28	1.313	2.055
	Kinematic	-0.015	-3.842	-7.398
		10.001	64.420	57.218
	SPP	0.272	-1.043	-7.887
		10.909	66.828	58.167
U-blox	Static	-0.009	-0.072	-0.011
		0.000	0.003	0.002
	Kinematic	-0.009	-0.073	-0.011
		0.015	0.04	0.065
	SPP	-0.009	-0.073	-0.011
		0.015	0.04	0.065

According to the Table 5 results are accurate more than precise for smartphone while u-blox provides better results in both concerning accuracy and precision during the same time.

For 30 minutes session the results of smartphone are better than previous session although it was shorter as shown in Table 8.

Table 8: Accuracy (upper line for each row) and precision (lower line) results considering a session length of 10 mins.

Device	Method	E(m)	N(m)	U(m)
Huawei	Static	0.283	-0.222	-0.295
		0.242	0.488	1.124
	Kinematic	0.253	-0.198	-0.223
		4.205	7.384	18.997
	SPP	0.253	-0.198	-4.025
		4.671	8.569	19.18
U-blox	Static	-0.017	-0.076	-0.105
		0.004	0.008	0.007
	Kinematic	0.098	0.010	0.058
		0.194	0.205	0.357
	SPP	1.249	2.77	-0.020
		1.921	5.119	4.818

Table 9: Accuracy (upper line for each row) and precision (lower line) results considering a session length of 10 mins.

Device	Method	E(m)	N(m)	U(m)
Huawei	Static	0.437	0.01	0.402
		0.189	0.783	0.797
	Kinematic	0.529	0.287	0.510
		3.584	7.795	14.788
	SPP	1.143	0.767	-2.597
		4.056	9.071	15.447
U-blox	Static	-0.254	-0.947	0.970
		0.385	0.195	1.404
	Kinematic	-0.262	-0.979	0.678
		4.630	6.600	19.21
	SPP	-0.248	-0.922	-3.437
		4.910	6.746	19.134

4.3 Real Time Kinematic Positioning

In case real time positioning, it is mandatory to have real time corrections broadcasted by one or more permanent station. In this work the SPIN GNSS Network (https://www.spingnss.it/spiderweb/frmIndex.aspx) has been used, considering the Virtual Reference Station (VRS) correction. For using both u-blox and smartphone contemporarily, it is necessary to have the GNSS Internet Radio software (https://igs.bkg.bund.de/ntrip/download) for obtaining the differential corrections near to the test site. This last software allows us to save the corrections in a text file, in order to provide both for the u-blox and smartphone. Then, the RTKLIB software, with the RTKNAVI tool, has used again for performing the NRTK positioning.

Two different measurement campaigns have been considered, with a session length of 10 and 5 minutes respectively. This choice is due to the time interval that a generic user can wait for obtaining a positioning accuracy of about 5 cm, as described in Dabove and Manzino (2014). Only the test site C (open-sky area) is considered because, as it is possible to see in Table 11, no epochs with phase ambiguities fixed as integer value (Teunissen and Verhagen, 2009) has been obtained using the smartphone. This does not happen in case the u-blox receiver is considered: as a result , in 93% of solutions the phase ambiguities are fixed as integer value and the accuracies are about 3-4 cm both for 2D and up component. Analysing the float solutions (float means that the phase ambiguities are non defined as integer values but are real numbers), the u-blox receiver provides precisions comparable to the fixed solutions while the accuracy is around 40 cm for 2D and up components.

Table 10: Real time positioning results using u-blox receiver and a session length of 10 mins.

Fix	83%		
	E(m)	N(m)	U(m)
Precision	0.004	0.005	0.013
Accuracy	0.034	0.012	0.041
Float	17%		
	E(m)	N(m)	U(m)
Precision	0.014	0.007	0.042
Accuracy	0.293	0.359	0.391

Table 11: Real time positioning results using Huawei receiver and a session length of 5 mins.

Fix	0%		
	E(m)	N(m)	U(m)
Precision	N/A	N/A	N/A
Accuracy	N/A	N/A	N/A
Float	100%		
	E(m)	N(m)	U(m)
Precision	3.089	2.677	4.888
Accuracy	4.822	3.184	5.516

The behaviour of smartphone results are completely different because the accuracies are between 3.18m and 5.52m while the precisions are from 2.67m up to 4.88. This means that, considering also previous studies (Dabove and Di Pietra, 2019) not all smartphone GNSS receivers provide the same results because the raw observations have different conditions of noise and accuracy. It could be interesting to perform the same tests in the future considering new GNSS chipset and the employment of new GNSS constellations and signals.

5 CONCLUSIONS

Until a few years ago, low cost sensors and smart technologies were considered as "mass-market" solutions, able to estimate a very approximate positioning and adapt only for navigation or geolocalization.

Nowadays, new technologies, new user requirements, new platforms (e.g., Android 8.0) and new challenges have allowed to bring in our hands a very powerful "geomatics" tool. The modern smartphones or mass-market receivers are able to reach very impressive quality, both in static or kinematic positioning, widening the doors to an enormous quantity of applications and research fields.

UAV, pedestrian positioning, unmanned ground vehicle, object tracking, security issues, are only a short list of possible domain where the quality reachable with these kind of sensors could be exhaustive.

The improvement is also allowed by the quality of the GNSS signals, the modern infrastructure dedicated to GNSS positioning (e.g. CORS, network, NRTK, etc.) and by the increasing interesting due to user communities and big players about the use of these technologies for high quality positioning.

In this paper, it is strongly demonstrated that the quality of the signals collected using these technologies is completely able to reach a good positioning. Surely, combining the sensors with a better external antenna, the performances could be better and other possible applications could be founded. We have presented the results obtained with only one smartphone: this is not expected to be the same concerning the performance of all smartphones, especially because in 2018 the first smartphone with dual-frequency multi constellation GNSS receiver has been released (Xiaomi Mi8). This study wants to show how different results can be the obtained in function of different positioning techniques, that can be chosen according to the precision and accuracy requested. Future steps will be to test the performances of other smartphones with other GNSS chipset installed inside in order to provide a deep overview about possible results obtainable today. Certainly, this will be done considering also the new instruments released on the market in these few last months.

If few years ago, smart technologies were only a tools for calling and chatting, today these tools are becoming a potential tools even for geomatics applications. In the next future, new constellations and signals promise us an improvement of the quality in terms of precision and performance. Therefore, this is only the first step of this new positioning revolution.

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