Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 63 (2019) 94–102

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Towards high accuracy GNSS real-time positioning with smartphones

Paolo Dabove *, Vincenzo Di Pietra

Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino, Corso Duca degli Abruzzi, 24 – 10129 Torino, Italy

Received 27 April 2018; received in revised form 13 August 2018; accepted 14 August 2018
Available online 25 August 2018

Abstract

The possibility to access undifferenced and uncombined Global Navigation Satellite System (GNSS) measurements on smart devices with an Android operating system allows us to manage pseudorange and carrier-phase measurements to increase the accuracy of real-time positioning. The goal is to perform real-time kinematic network positioning with smartphones, evaluating the positioning accuracy regarding an external mass-market device. The positioning of Samsung Galaxy S8+ and Huawei P10 plus smartphones was performed using a dedicated tool developed by the authors, considering a continuous operating reference station (CORS) network with a mean inter-station distance of about 50 km. The same positioning technique was also applied to an external GNSS low-cost single-frequency receiver (u-blox EVK-M8T) to compare performance between the receiver and antenna embedded in the previous smartphones and this low-cost receiver coupled with a mass-market antenna (Garmin GA38). Attention was also focused on the phase ambiguity resolution, that it is still a challenging aspect for mass-market devices: even if the two smartphones provide slightly different results, the accuracy obtainable today is greater than 60 cm with a precision of few centimetres in real-time, if a CORS network is available. For real-time applications using portable devices, decimetre-level accuracy is sufficient for many applications, such as rapid mapping and search and rescue activities: these results will open new frontiers in terms of real-time positioning with portable low-cost devices.

Keywords: Smartphones; Real-time positioning; NRTK; GNSS positioning; Mass-market devices

1. Introduction

In recent years, the Global Navigation Satellite System (GNSS) real-time kinematic (RTK) networks have played a key role in the field of geomatics to be of significant use in numerous applications that go beyond the purely topographic and geodetic fields. The application landscape is huge; precision farming (Zhang et al., 2002), autonomous navigation, maritime survey (Moore et al., 2008), and environmental monitoring (Cina and Piras, 2015) are only a few examples.

The straightforward advantages offered by the network real-time kinematic (NRTK) positioning are, from a technical point of view, the modelling of the error sources that occur in RTK positioning, which are mainly tropospheric, ionospheric, and orbit errors to the phase ambiguity resolution.

The appearance of the GNSS continuous operating reference station (CORS) networks has increased both the reliability of the system and the accuracy of real-time positioning, allowing the spread of mass-market single-frequency GNSS receivers (Manzino and Dabove, 2013) for precise positioning. In fact, with only 200€, it is possible to buy a GNSS receiver (e.g., u-blox, as described by Manzino and Dabove, 2013) coupled with a low-cost antenna (e.g., Garmin GA38; Dabove and Manzino, 2014) that allows reaching a level of accuracy of a few centimetres in real time. Numerous researchers have already investigated the evaluation of the accuracy and performance of NRTK positioning in mass-market receivers

* Corresponding author.
E-mail addresses: paolo.dabove@polito.it (P. Dabove), vincenzo.dipietra@polito.it (V. Di Pietra).

https://doi.org/10.1016/j.asr.2018.08.025
0273-1177/

(Dabove et al., 2014), but what is interesting now is to analyse the performance obtainable today using portable devices that are already in the hands of people: smartphones.

Nowadays, smartphone technology allows the user to locate their position, exploiting the embedded sensors of the devices, such as GNSS chipsets, antennas, INS, etc. All the data acquired by these sensors are integrated into a unique solution where the weight of each data is usually unknown. If this integration allows saving power and optimising the application functionalities, it does not give a real controlled positioning solution.

Several studies have been performed to verify the feasibility (Humphreys et al., 2016) and positioning accuracy (Pesyna et al., 2014) with smartphones for different purposes, from urban (Masiero et al., 2014; Wang et al., 2015; Wang et al., 2016a,b; Adjrad and Groves, 2017) to pedestrian positioning applications (Al-Azizi and Shafri, 2017; Fissore et al., 2018), always facing the problems of high-level application programming interface (API) and the filtered measurements provided by the GNSS chipset. Moreover, with this kind of output, all the processing procedures with standard GNSS positioning software were not usable.

Fortunately, from 2016, with the new operating system (OS) Android Nougat 7.0, Google has permitted direct access to the raw measurements of the GNSS chipset mounted on some Android-based smartphones. In this context, it is interesting to test the capability of the smartphone technology for real-time positioning applications. The goal of this work is not only to demonstrate the possibility to exploit the embedded GNSS chipset and the OS features to access the raw data for positioning but also to analyse the accuracy and precision obtainable if NRTK positioning is performed. Of course, the goal is not to reach a centimetre-level accuracy because the user often does not know where the GNSS antenna is inside the smartphone. This work is aimed to show whether it is possible to obtain real-time corrections to reach a sub-metre level of accuracy.

Starting from an overview of the smartphone capabilities for GNSS positioning, two Android-based devices, the Samsung Galaxy S8+ and the Huawei P10 plus, have been described. Then, a description of the NRTK services available today in the test context is presented, and the test setup and hardware have been illustrated. Finally, the processing operations and result discussion will conclude this article.

2. Smartphones

Nowadays, the advance in the computational power and miniaturisation of chipsets have permitted the use of smartphone technology not only as a communication device but also as real-time positioning and navigation tools usable in a wide range of applications. The smartphone user location can be defined using the single-frequency GPS/GNSS built-in chipset and the connected smartphone antenna. There are many chipsets available on the market, with the leading manufacturers represented by Qualcomm, Broadcom, u-blox, MediaTek, and STMicroelectronics. Regarding the antenna, different gain patterns and structures have been used in the past years, usually preferring low-cost patch antennas.

Usually, the GNSS chipset is in a system of chipsets (SoCs) containing the computational unit and other chipsets used for assisting and empowering smartphone location capability. Assisted GNSS (A-GNSS) uses standard GNSS data from the built-in chipset and predicts ephemeris data (broadcasted using mobile networks) to eliminate sections of the signal search space (Zandbergen and Barbeau, 2011). The SoCs can improve the GNSS positioning by other position augmentation sources (i.e., by INS, barometer, altimeter, etc.) or could apply some filtering to force the position solution. As state of the art, the previous systems can provide an inner stand-alone solution with an accuracy of between 25 (GNSS only) and 5 m (A-GNSS) (Tomaštík et al., 2017).

Using clocks, orbits, and atmospheric models to improve ranging measurements, it is possible to achieve 2- to 3-metre-accurate positioning under good multipath conditions if SoCs are considered for real-time stand-alone positioning. In fact, the sensitivity of the antenna is strongly influenced by the noise induced by the front-end and the reflections of the surfaces. In these cases, the accuracy degrades to 20 m or worse. Moreover, the filtering algorithms used in the SoCs are not appropriate for some applications where a centimetre-level accuracy is needed. From a geodetic point of view, directly accessing the raw data acquired by the GNSS chipset is mandatory to answer to the following question: 'What is the accuracy of the smartphone GNSS receivers?'

The optimal procedure to answer to this question is to use the raw measurements acquired by the GNSS receiver and to process these in both static and kinematic conditions. Unfortunately, until 2016, no GNSS raw data acquired by a mobile platform were available. In fact, high-level APIs, such as Android and iOS, do not permit direct access to the acquired data that comes from internal sensors. However, on May 2016, during the I/O conference, Google announced the possibility to extract pseudoranges and carrier-phase measurements from smartphones with Android 7.0 OS. The new Android devices can acquire data from all the satellite constellations and provide the following data:

- Pseudoranges and pseudorange rates.
- Navigation messages.
- Accumulated delta ranges or carriers.
- Hardware clocks.

Moreover, on September 21, 2017, Broadcom announced the world's first mass-market, dual-frequency GNSS receiver device, the BCM47755. It is a very strong innovation, destined to bring a revolution in the field of survey and geo-localisation. With these kinds of sensors, accuracy of a few centimetres could be obtainable even with mobile devices (Jeong et al., 2018).

2.1. Characteristic of smartphones

We considered a Samsung Galaxy S8+ and a Huawei P10 plus to evaluate the performances of NRTK positioning of the embedded GNSS receivers. Both devices have the OS Android Nougat 7.0 and can collect GPS, GLONASS, Galileo, and BEIDOU constellations through an equipped Broadcom Limited Galileo-enabled BCM4774 GNSS chipset. The exact GNSS antenna specifications and positions are unknown even if is possible to state that they are mounted in the upper part of the phone (see Table 1).

Most devices manufactured in 2016 or later with Android 7.0 or higher provide raw GNSS data, as shown in Table 2.

Table 1
Specification of the tested smartphone.

Name	Samsung Galaxy S8+	Huawei P10 Plus
OS	Android 7.0 (Nougat)	Android 7.0 (Nougat), planned upgrade to Android 8.0 (Oreo)
Chipset	Exynos 8895 Octa – EMEA	HiSilicon Kirin 960
CPU	Octa-core (4 × 2.3 GHz & 4 × 1.7 GHz) – EMEA	Octa-core (4 × 2.4 GHz Cortex-A73 & 4 × 1.8 GHz Cortex-A53)
GPU	Mali-G71 MP20 – EMEA	Mali-G71 MP8
GNSS	Yes, with A-GPS, GLONASS, BDS, Galileo	Yes, with A-GPS, GLONASS, BDS, Galileo
Sensors	Accelerometer, gyro, proximity, compass, barometer, heart rate, SpO2	Accelerometer, gyro, proximity, compass

Table 2
List of smartphones that support raw GNSS measurements.

Model	Android Version	Pseudorange data	Navigation messages	Accumulated delta range	Hardware clock	Global navigation systems
Huawei Honor 9	7	yes	yes	yes	yes	GPS GLONASS
Samsung S8 (Exynos)	7	yes	yes	yes	yes	GPS GLONASS Galileo BDS
Samsung S8 (QCOM)	7	yes	no	no	yes	GPS
Huawei P10	7	yes	yes	yes	yes	GPS GLONASS Galileo BDS
Huawei P10 Lite	7	yes	no	no	yes	GPS
Huawei Honor 8	7	yes	yes	yes	yes	GPS GLONASS BDS
Huawei Mate 9	7	yes	yes	yes	yes	GPS GLONASS BDS
Huawei P9	7	yes	yes	yes	yes	GPS GLONASS BDS
Pixel XL	7	yes	no	no	yes	GPS
Pixel	7	yes	no	no	yes	GPS
Nexus 6P	7	yes	no	no	no	GPS
Nexus 5X	7	yes	no	no	no	GPS
Nexus 9 (non-cellular version)	7.1	yes	yes	yes	yes	GPS GLONASS
Pixel 2 XL	8	yes	no	no	yes	GPS GLONASS Galileo BDS QZSS
Pixel 2	8	yes	no	no	yes	GPS GLONASS Galileo BDS QZSS

3. NRTK positioning

Nowadays, with the spread of the NRTK positioning technique, it is possible to perform real-time and post-processing positioning all over the country without a master receiver, obtaining high accuracy and precision in the function of the rover equipment. An RTK network is a network of GNSS permanent stations whose data are used to generate corrections for rovers located inside the network.

Today, NRTK operates in several countries, such as Germany, Spain, England, Italy, China, some areas of the United States, Australia, and so on. Networks can have different extensions from small local networks with a mean inter-station distance of about 40–50 km to networks covering entire countries with mean inter-station distances of about 100–150 km, as described by Dabove et al. (2014).

Generally, the network infrastructure consists of three segments. The first is composed of the so-called GNSS CORS networks, well-known located receivers spread across the territory to generate a distributed web. The second segment is the control centre, which collects and processes the data captured by the CORSs and broadcasts the differential corrections and saves the raw data for post-processing activities. Specifically, it fixes the ambiguity of all satellites for each permanent station and calculates ionospheric and tropospheric delays. Through different interpolation models, it can provide calculated corrections to every point within the network. Such corrections can be sent in real time or can be used to create a virtual RINEX for a post-processing approach. The third part of this system is composed of the products generated by the control centre that can be sent to the users that rely on the service (Wang et al., 2016a,b). The users, after a subscription, obtain RTK corrections that can be generated by several methods:

- Virtual reference station (VRS);
- Multi-reference station (MRS);
- Master-auxiliary corrections (MAX or MAC);
- Flächen-Korrektur-Parameter (FKP);
- Nearest station (NRT).

Among them, only the VRS and the NRT services allow performing NRTK positioning with single-frequency receivers. These extend the capabilities of mass-market receivers and low-cost GNSS chipsets to reach sub-metric real-time positioning. Of course, this is possible only if the phase ambiguities are declared as “fixed”: it means that the ambiguities are estimated as integer value, so it is possible to speak of fixed (‘fix’) solutions. Otherwise, without ambiguity fixing, only float solutions are available with sub-meter accuracies. As described in Dabove and Manzino (2017), the phase ambiguity fixing is a common practice for geodetic receivers: this not happens for mass-market receivers for one main reason. In general, geodetic receivers are able to track more than one frequency, so they can exploit some techniques (e.g. wide-lane) as described in Cocard and Geiger (1992) that allow to fix the phase ambiguities quickly and in a more correct way. In this context, it is critical to consider these aspects, especially when a centimetre accuracy is required in real-time applications.

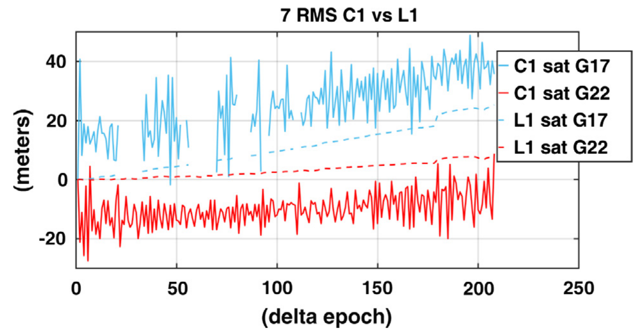

Fig. 1. RMS of pseudorange and carrier-phase measurements for two GPS satellites: the G17 and G22 are satellites with the highest and lowest elevations during the survey, respectively.

In this paper, it has been decided to do not consider the DGNSS technique due to the noise of pseudorange measurements compared to the carrier-phase measurements, as seen in Fig. 1.

4. Test setup

As already stated in the introduction, the main limiting factor to process raw measurements acquired by new smartphone devices is that the user does not know whether the used measurements are pre-filtered. In this context, a tool has been developed that can obtain the raw measurements obtained directly from the device and compute an RTK positioning using the differential corrections provided by a CORS network. Moreover, for post-processing purposes, the proposed Google-developed logger is not able to save the data directly in a receiver independent exchange (RINEX) compatible format but only to retrieve the cumulated delta range expressed in terms of a constant (i.e., the wavelength) that multiplies the carrier phase expressed in cycles (Cameron et al., 2015).

Starting from these, a MATLAB code has been developed that stores the raw data acquired by the GNSSLogger app in a RINEX format. Moreover, the app GEO++ RINEX Logger, released in August 2017 (available at http://www.geopp.de/logging-of-gnss-raw-data-on-android/) was able to acquire and store the GNSS measurement in RINEX format directly. In this context, both applications were installed on the two tested smartphones: the Samsung Galaxy S8+ and the Huawei P10 plus.

For these tests, the Servizio di Posizionamento Interregionale GNSS Piemonte–Lombardia (SPIN) GNSS CORS network (https://www.spingnss.it/spiderweb/frmIndex.aspx) was considered. This network is managed by Leica GNSS Spider software and allows obtaining differential corrections for a user through the network transport of RTCM via Internet protocol (NTRIP) authentication after a free registration. This network, as shown in Fig. 2, has a

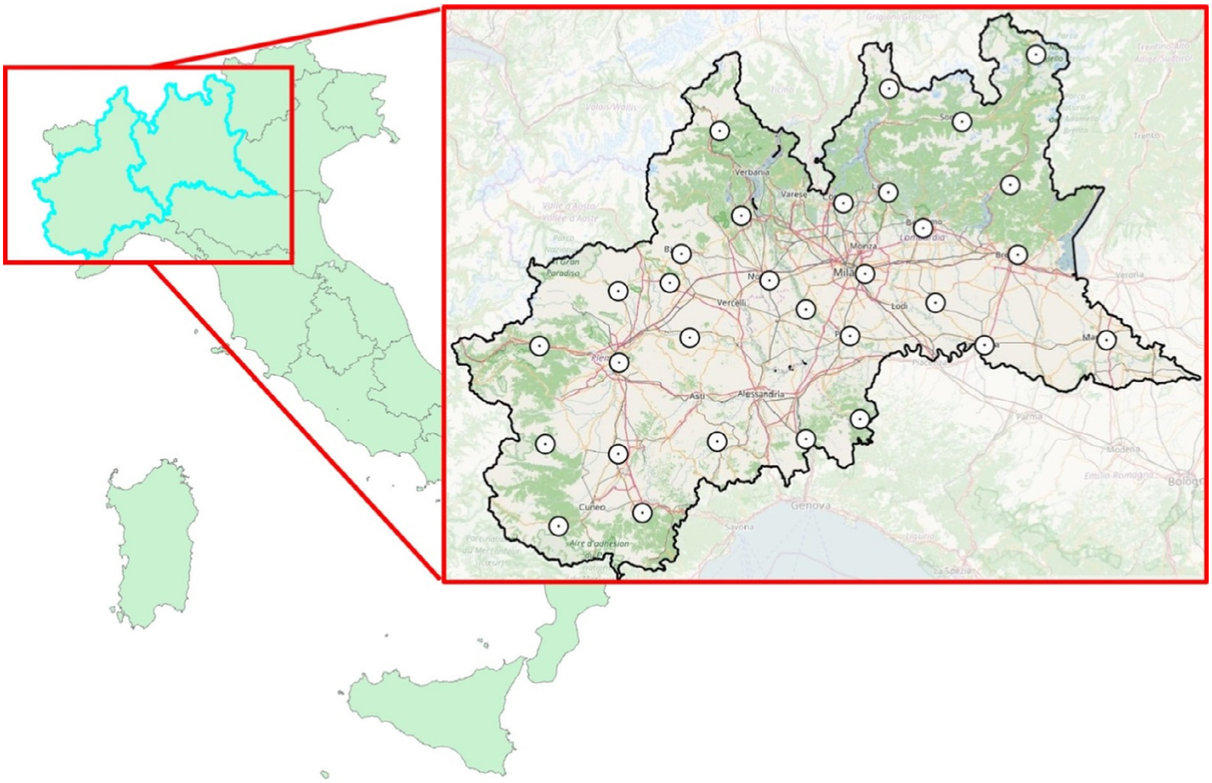

Fig. 2. The SPIN GNSS network used for NRTK positioning.

mean inter-station distance of about 50 km and is used for real-time and post-processing applications. The coordinates of all stations are obtained from a network adjustment computed with the Bernese GPS 5.0 software in the ETRF2000 reference frame (Altamimi, 2010; Altamimi, 2017).

The rover test site has been chosen at a well-known point located in an outdoor rooftop of the Department of Environment, Land and Infrastructure Engineering (coordinates: 45.063304798 N, 7.660465262 E, 306.7413 h in the ETRF2000 reference frame) at Politecnico di Torino (Italy). This rover site is less than 1 km from the nearest CORS (TORI), a permanent station belonging to the EUREF network (http://www.epncb.oma.be/). The GNSS raw measurements were collected for 10 min in different sessions during October and November 2017, repeated for 2–3 days, considering a sampling rate of 1 Hz. The entire conditions around the smartphones have been considered, such as the approximated location of the antenna in the smartphone, building obstructions, etc. During the smartphone acquisitions, a u-blox LEA-M8T GNSS receiver has been co-located coupled with a Garmin GA-38 antenna in a fixed, static, repeatable point, as shown in Fig. 3.

Fig. 3 shows the point where the GNSS Garmin antenna is installed, and the place where the smartphones is located is not the same. For the result analysis, this level arm is considered both for horizontal (23.6 cm) and up (13.7 cm) components. Thus, the results shown in the following section refer to the same point, that is, where the Garmin antenna is installed.

Since some u-blox chipsets are installed inside smartphones, the external u-blox receiver is used to compare the smartphone solutions with those provided by this external low-cost system. In this case, the u-blox receiver is set to provide the raw GNSS measurements on L1 frequency. Using the RTKLIB v.2.4.3 b29 open-source software, it was possible to collect:

- Undifferenced and uncombined measurements (i.e., pseudoranges and carrier phase on L1 frequency) for post-processing purposes;
- NRTK solutions considering differential corrections, such as VRS and NRT;
- Stream of RTK differential corrections.

As previously stated, an experimental smartphone application created by the authors has been developed and used to compute the smartphone NRTK positioning using VRS and NRT corrections. From a numerical point of view, no substantial differences can be obtained considering one correction or the other. Thus, the following results are referred to the VRS correction.

In order to compare the performances of smartphones GNSS receivers with those obtainable with the u-blox, the application used for smartphone positioning considers the same algorithm for the ambiguity resolution that is available inside the RTKLIB software. This algorithm is

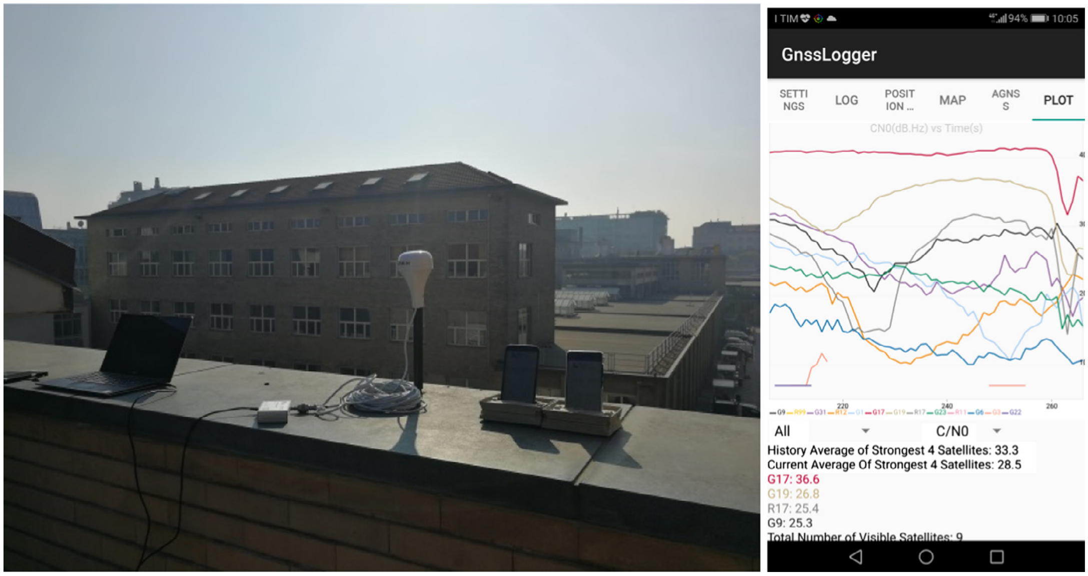

Fig. 3. Rover test site: on the left, the external GNSS Garmin GA38 antenna installed on the roof of a building with the two different smartphones considered, while on the right, the smartphone app is running.

based on the on-the-fly (OTF) integer ambiguity resolution method, where the values of integer ambiguities are obtained by solving an ILS (integer least square) problem thanks to a well-known efficient search strategy LAMBDA (Teunissen, 1995) and its extension MLAMBDA (Chang et al., 2005). Moreover, a ratio factor of "ratio test" for standard integer ambiguity validation strategy has been considered. This factor, that can be considered also as threshold, means the ratio of the squared sum of the residuals with the second best integer vector to with the best integer vector. So, when the inequality $\sigma^2_{02nd}/\sigma^2_{01st} \geqslant ratio$ is satisfied, the ambiguities are defined as integer values, so it is possible to define that solution as "fix", otherwise as "float". For these first experiments, the threshold value is set equal to 3, following previous studies (Dabove and Manzino, 2017).

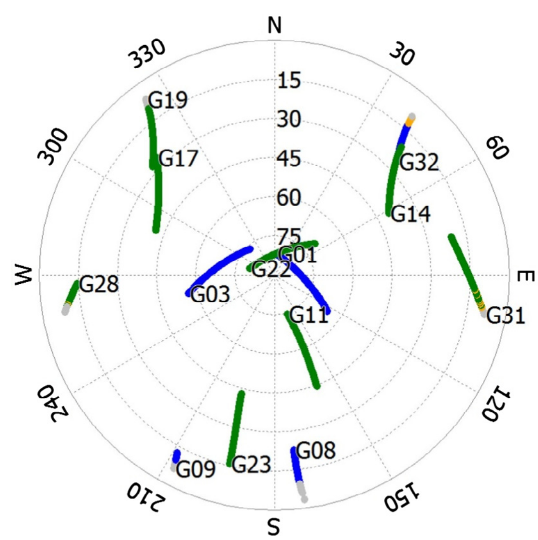

Fig. 4. Sky plot of GPS visible satellites: An overview of the satellite geometry.

5. Experimental results

As discussed in the previous section, both smartphones and the u-blox receiver have been installed on the roof of a building in an open-sky area. For each epoch, Fig. 4 shows that it was possible to track 10 GPS and 5 GLONASS satellites, respectively, obtaining a maximum GDOP value equal to 2.3.

From a quality point of view of the signals, it is possible to note (Fig. 5) that, in some cases, the quality is not good, even if the cutoff angle is chosen equal to 10°. It happens that the signal to noise ratio (SNR) value is less than 25 dB-Hz, defining the satellite signal as too noisy to be processed. In this context, only satellites with an SNR value greater than 30 dB-Hz and with an elevation greater than 15° are considered. Applying these filters, the number of available satellites decreases to 12: 8 GPS and 4 GLONASS. Also analysing the difference over time of

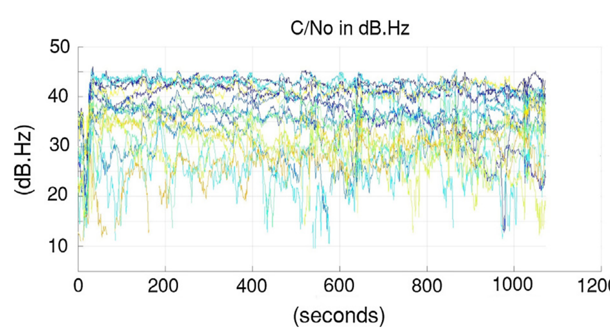

Fig. 5. SNR values with respect to the satellite elevations – GPS-only constellation.

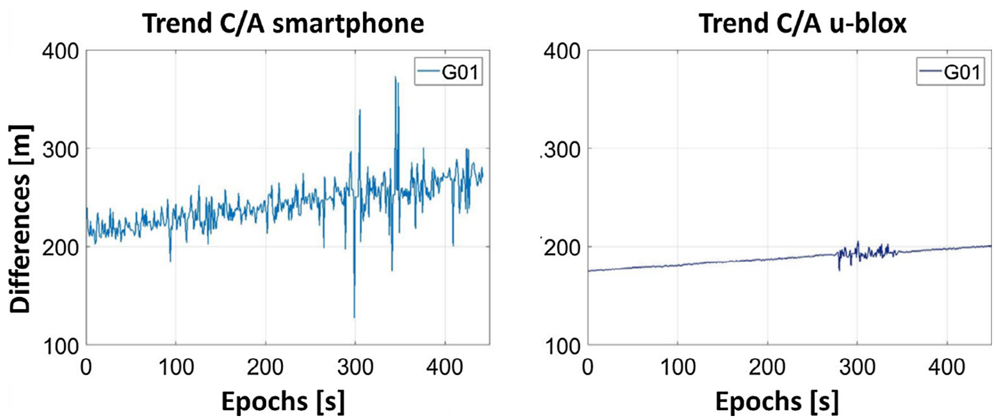

Fig. 6. Comparison of code measurement noise between smartphone and u-blox raw data.

pseudorange measurements it is possible to understand how the u-blox data are less noisier than the smartphone ones. In Fig. 6 the trend of the pseudorange measurements of a generic satellite (G01) is shown: this has been obtained considering the pseudorange measurement at epoch *t* minus the measurement at epoch *t-1* both for smartphone and u-blox receiver. In this case, no substantial differences can be obtained between the two considered smartphones, as also summarized in Table 3.

After these preliminary considerations, in Figs. 7 and 8, it is possible to see the trend of the difference between NRTK coordinates estimated in real time with respect to the reference ones. The green and blue points refer to solutions in which the phase ambiguities can be declared as ‘fixed’ or “float”, respectively. In case of ‘fix’ solutions, the differences with respect to the reference coordinates are greater than the ‘float’ solutions. When the algorithm tries to fix the phase ambiguities, the solution becomes worse. This is maybe due to the quality of the smartphone measurements, that are more noisier than those obtainable with the u-blox receiver. Indeed, the software encounter some difficulties to fix the phase ambiguities in a correct way, and this is also confirmed if the time series analysis of the ratio value is analysed: as shown in Fig. 9, it is possible to see both the high variability in time of this estimation and the few cases where the ratio value is greater than the threshold, if compared to those obtained with the u-blox receiver.

Increasing the threshold value, the percentage of the ‘fix’ solution decreases close to zero, but the quality in terms of differences between estimated and reference coordinates

Table 3
RMS values for pseudorange and carrier-phase measurements for smartphones and u-blox receiver.

	RMS of pseudorange	RMS of carrier-phase
P10 plus	3,86 m	9,14 m
S8+	4,11 m	7,23 m
u-blox	0,83 m	0,21 m

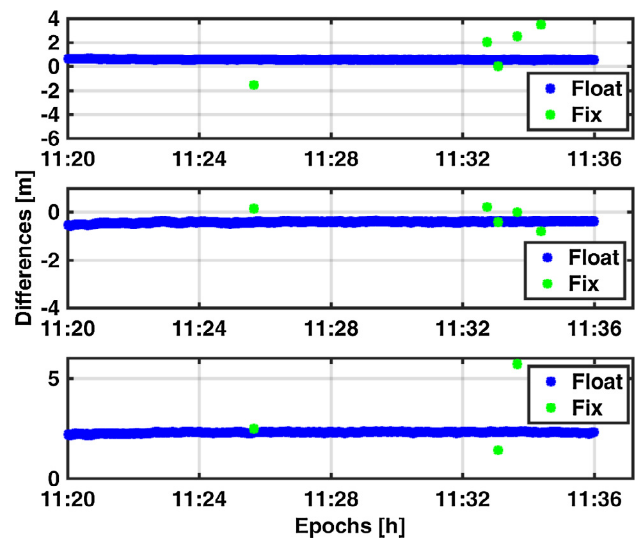

Fig. 7. Positioning performances of Samsung Galaxy S8+; from the top to the bottom of the figure represents the behaviour of the East, North, and Up components with respect to the reference values.

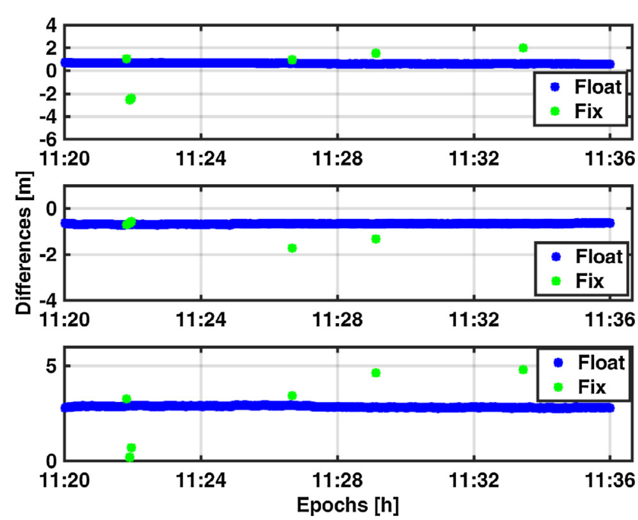

Fig. 8. Positioning performances of P10 plus; from the top to the bottom of the figure represents the behaviour of the East, North, and Up components with respect to the reference values.

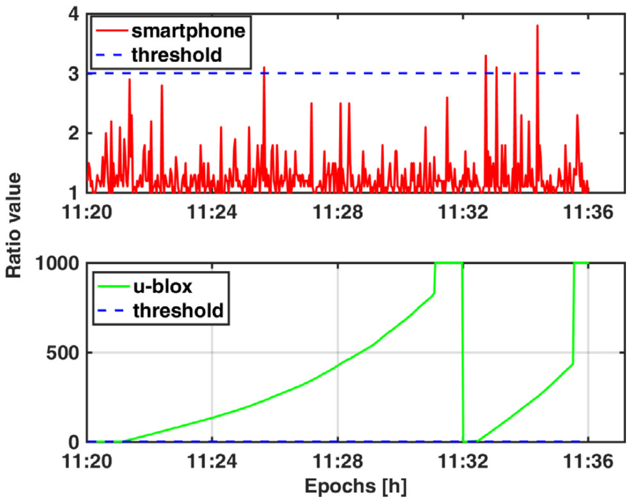

Fig. 9. Time series analysis of the ratio value considering smartphone and u-blox receivers.

Table 4
Statistical parameters related to the differences between estimated (NRTK) and reference coordinates considering GPS + GLONASS constellations.

	S8+		P10 plus	
	Mean [m]	Std [m]	Mean [m]	Std [m]
East	−0.200	0.078	−0.741	0.043
North	0.923	0.061	1.517	0.040
up	2.336	0.092	2.604	0.071

increases. In Table 4, the most significant statistical parameters are summarised.

Table 4 shows that the two different smartphones provide quite different results. If the Samsung Galaxy S8+ gives a mean 2D value less than a metre, the differences related to the P10 plus are over 1.50 m. In both cases, the standard deviations are about few centimetres; therefore, there are no gross errors and the solution is precise even if inaccurate.

Considering the GPS-only solution, it is possible to improve the accuracy and precision. Table 5 shows that both smartphones obtain a 2D accuracy around 60 cm with a standard deviation of a couple of centimetres. Thus, for these kinds of receivers, the multi-constellation approach does not provide any benefit if NRTK positioning is computed. Comparing these results with those obtainable

Table 5
Statistical parameters related to the differences between estimated (NRTK) and reference coordinates, considering only the GPS constellation.

	S8+		P10 plus	
	Mean [m]	Std [m]	Mean [m]	Std [m]
East	−0.260	0.037	−0.686	0.023
North	0.532	0.026	0.616	0.036
up	2.452	0.046	2.853	0.052

Table 6
Statistical parameters related to the u-blox NRTK solutions with respect the reference coordinates.

	u-blox	
	Mean [m]	Std [m]
East	0.002	0.004
North	−0.001	0.004
Up	0.009	0.006

with the u-blox receiver and Garmin antenna, it is possible to note a completely different behaviour in terms of accuracy. The u-blox provides excellent results, comparable to those available in the literature (Dabove and Manzino, 2014; Cina and Piras, 2015) as seen in Table 6.

6. Conclusions

From this study, it is confirmed that it is possible to perform NRTK positioning with smartphones. It is not so easy to reach an accuracy of a few centimetres because in addition to some problems such as multipath and imaging effects, one of the main issues is still to know where the GNSS antenna is inside the smartphone. In most cases, this information is unavailable. Thus, the real problem is to know the exact position of the smartphone antenna. While the chipset position is quite well represented in the manufacturer schemas, the antenna position is usually not highlighted. Therefore, we should make some assumptions. One could be to approximate the position on the centre of the smartphone. The assumption made in this article is to consider the size of the smartphone as the tolerance for the precision of positioning. The phase-centre identification of the smartphone GPS antenna will be a subject of other research. In this context, it does not make sense to try to fix the phase ambiguities. It is better to have a good 'float' solution rather than a bad 'fix' solution (Teunissen and Verhagen, 2009; Dabove and Manzino, 2014). In this context, a dedicated tool has been developed by the authors that allows performing NRTK positioning while considering a threshold for the ambiguity fixing method. Two different smartphones, with different internal chipsets have been tested in a CORS network with a mean inter-station distance of about 50 km, considering both VRS and nearest corrections. The results have shown satisfactory performance in terms of precision but not from the accuracy perspective. Even if the two smartphones provide slightly different results, the accuracy obtainable today is greater than 1 m with a precision of few centimetres, especially if only the GPS constellation is considered. These results will open new frontiers in terms of real-time positioning with portable devices, especially for rapid mapping or emergency situations. In the future, it will be interesting to test single-base RTK positioning, considering a mass-market master station, to analyse what happens if the rover user is located where the NRTK positioning is not available due to the lack of a CORS network.

References

Adjrad, M., Groves, P.D., 2017. Intelligent urban positioning: integration of shadow matching with 3D-mapping-aided GNSS ranging. J. Nav. 71 (1), 1–20. https://doi.org/10.1017/S0373463317000509 (in press).

Al-Azizi, J.I., Shafri, H.Z.M., 2017. Performance evaluation of pedestrian locations based on contemporary smartphones. Int. J. Navig. Obs. 2017, 1–11. https://doi.org/10.1155/2017/6750346.

Altamimi, Z., 2010. ITRF2008 and transformation to ETRF2000. In: EUREF Symposium.

Altamimi, Z., 2017. EUREF Technical Note 1: Relationship and Transformation between the International and the European Terrestrial Reference Systems. Institut National de l'Information Géographique et Forestière (IGN), France.

Cameron, A., Litton, J.D., Langenstein, T., Hatch, R., & Reynolds, T., 2015. Accuracy in the Palm of Your Hand 16.

Chang, X.W., Yang, X., Zhou, T., 2005. MLAMBDA: a modified LAMBDA method for integer least-squares estimation. J. Geodesy 79 (9), 552–565. https://doi.org/10.1007/s00190-005-0004-x.

Cocard, M., and Geiger, A. Systematic search for all possible widelanes. In: Proceedings of the 6th International Geodetic Symposium on Satellite Positioning, 1992, pp. 312–318.

Cina, A., Piras, M., 2015. Performance of low-cost GNSS receiver for landslides monitoring: test and results. Geomatics Natl. Hazards Risk 6 (7), 497–514. https://doi.org/10.1080/19475705.2014.889046.

Dabove, P., Manzino, A.M., 2014. GPS & GLONASS mass-market receivers: positioning performances and peculiarities. Sensors 14 (12), 22159–22179. https://doi.org/10.3390/s141222159.

Dabove, P., Manzino, A.M., 2017. Artificial neural network for detecting incorrectly fixed phase ambiguities for L1 mass-market receivers. GPS Solut. 21 (3), 1213–1219. https://doi.org/10.1007/s10291-017-0605-x.

Dabove, P., Manzino, A.M., Taglioretti, C., 2014. GNSS network products for post-processing positioning: limitations and peculiarities. Appl. Geomatics 6 (1), 27–36. https://doi.org/10.1007/s12518-014-0122-3.

Fissore, F., Masiero, A., Piragnolo, M., Pirotti, F., Guarnieri, A., Vettore, A., 2018. Towards Surveying with a Smartphone. New Advanced GNSS and 3D Spatial Techniques. Lecture Notes in Geoinformation and Cartography. https://doi.org/10.1007/978-3-319-56218-6_13.

Humphreys, T.E., Murrian, M., van Diggelen, F., Podshivalov, S., Pesyna, K.M., 2016. On the feasibility of cm-accurate positioning via a smartphone's antenna and GNSS chip. In: Proc. IEEE/ION PLANS, Institute of Navigation, Savannah, Georgia, USA, April 11–14, IEEE, pp. 232–242.

Jeong, J.P., Yeon, S., Kim, T., Lee, H., Kim, S.M., Kim, S.C., 2018. SALA: Smartphone-assisted localization algorithm for positioning indoor IoT devices. Wireless Netw. 24 (1), 27–47. https://doi.org/10.1007/s11276-016-1309-9.

Manzino, A.M., Dabove, P., 2013. Quality control of the NRTK positioning with mass-market receivers. Global Positioning Systems: Signal Structure, Applications and Sources of Error and Biases, 17–40, ISBN: 978-1-62808-022-3.

Masiero, A., Guarnieri, A., Pirotti, F., Vettore, A., 2014. A particle filter for smartphone-based indoor pedestrian navigation. Micromachines 5 (4), 1012–1033. https://doi.org/10.3390/mi5041012.

Moore, T., Hill, C., Norris, A., Hide, C., Park, D., Ward, N., 2008. The potential impact of GNSS/INS integration on maritime navigation. J. Nav. 61 (2), 221–237. https://doi.org/10.1017/S0373463307004614.

Pesyna Jr, K.M., Heath Jr, R.W., Humphreys, T.E., 2014. Centimeter positioning with a smartphone-quality GNSS antenna. In: Proc. ION GNSS 2014, Institute of Navigation, Tampa, Florida, USA, September 8–12, pp. 1568–1577.

Teunissen, P.J., 1995. The least-squares ambiguity decorrelation adjustment: a method for fast GPS integer ambiguity estimation. J. Geodesy 70 (1–2), 65–82. https://doi.org/10.1007/BF00863419.

Teunissen, P.J.G., Verhagen, S., 2009. GNSS carrier phase ambiguity resolution: challenges and open problems. Observing our changing Earth, 785–792. https://doi.org/10.1007/978-3-540-85426-5_90.

Tomaštík, J., Saloň, Š., Piroh, R., 2017. Horizontal accuracy and applicability of smartphone GNSS positioning in forests. Forestry: Int. J. Forest Res. 90 (2), 187–198. https://doi.org/10.1093/forestry/cpw031.

Wang, L., Groves, P.D., Ziebart, M.K., 2015. Smartphone shadow matching for better cross-street GNSS positioning in urban environments. J. Nav. 68 (3), 411–433. https://doi.org/10.1017/S0373463314000836.

Wang, L., Li, Z., Zhao, J., Zhou, K., Wang, Z., Yuan, H., 2016a. Smart device-supported BDS/GNSS real-time kinematic positioning for sub-meter-level accuracy in urban location-based services. Sensors 16 (12), 2201.

Wang, L., Li, Z., Yuan, H., Zhao, J., Zhou, K., Yuan, C., 2016b. Influence of the time-delay of correction for BDS and GPS combined real-time differential positioning. Electron. Lett. 52 (12), 1063–1065.

Zandbergen, P.A., Barbeau, S.J., 2011. Positional accuracy of assisted GPS data from high-sensitivity GPS-enabled mobile phones. J. Nav. 64 (3), 381–399. https://doi.org/10.1017/S0373463311000051.

Zhang, N., Wang, M., Wang, N., 2002. Precision agriculture-Aworldwide overview. Comput. Electron. Agric. 36 (2), 113–132. https://doi.org/10.1016/S0168-1699(02)00096-0.