Perspective

Recent advances and perspectives for positioning and applications with smartphone GNSS observations

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1. Introduction and motivation

There are a number of location-based services and applications which take advantage of GNSS (Global Navigation Satellite System). These include mobile applications run on ‘smart’ devices, which support many personal activities and address the needs of both society and the market [1–4]. However, the initial intention of GPS system development was to provide an absolute and instantaneous navigation and positioning capability in a global terrestrial reference frame. Primarily, the system was designed to ensure an accuracy level of a few metres for authorised users, and an accuracy level 1–2 orders of magnitude lower for unauthorised users, using observations from at least four satellites and broadcast ephemeris [5, 6]. However, in the past few decades, we have witnessed remarkable advances in GNSS technology, in terms of satellite constellation deployment, receiver design, and processing algorithms. This progress has, in turn, significantly enhanced the performance of positioning, and expanded the scope of GNSS applications.

The modernisation of existing GNSS systems, and the development of new systems, have seen us move towards a new stage of multi-constellation and multi-frequency observations. Among the most important advances in this regard were the introduction of the L5 band in GPS satellites from Block IIF, and the change from FDMA (frequency division multiple access) to CDMA (code division multiple access) in the GLONASS system, which lends itself to a higher level of interoperability and consistency with other systems. Several GLONASS-M and GLONASS-K satellites have been transmitting CDMA signals on the L3 band since February 2011, when the first GLONASS-K1 SVN 801 satellite was launched [7–9]. Further modernisation of GLONASS will introduce signals on frequencies overlapping with these in other constellations, e.g. GPS L1 and L5 bands [10]. As recent studies have shown, L3 CDMA GLONASS signals are clearly beneficial in terms of the ambiguity resolution of phase signals [11].

After an initial delay in the deployment of the Galileo constellation, recent years have seen great progress in the population of orbital planes with satellites, and the system is now making rapid progress towards Full Operational Capability (FOC). With the advent of FOC, Galileo constellation will comprise 30 satellites evenly spread on three medium earth orbits. This will include 24 operational and two spare satellites for each plane, which defines the Walker constellation [12, 13]. Since the declaration of initial services made in December 2016, Galileo has been providing positioning, navigation, and timing (PNT) services on a global scale with four frequency bands, namely E1, E5a, E5b, and E6, using 22 FOC and
4 IOV (In-Orbit-Validation) satellites [13–18]. The current constellation includes two satellites unexpectedly injected into highly eccentric orbits [19]. Fortunately, it is still fully feasible to employ these two satellites in a variety of engineering and scientific applications, provided that precise orbits and clocks are used [20–22].

A much faster rate of progress in terms of satellite deployment, and thus system development, can be observed in the case of Chinese BeiDou Navigation Satellite System (BDS). Following BeiDou phase 1 and phase 2 (two intermediate steps responsible for system demonstration and regional service, respectively), a global PNT service has been provided, with the completion of BeiDou phase 3, since 27 December 2018 [23–26]. This recent modernisation introduced new signals, namely B1C, B2a, and B2b. Support from regional and augmentation systems such as Quasi-Zenith Satellite System (QZSS) and the Indian Regional Navigation Satellite System (IRNSS) has resulted in a significant increase in availability, integrity, reliability, and accuracy of positioning with GNSS [27, 28]. With these recent advancements, GNSS is now considered as a fully mature space measurement technique. Although much significant progress has been made, there are now new challenges facing researchers, such as e.g. proper stochastic modelling of multi-GNSS observations, inter-system and inter-frequency bias handling, and the development of effective functional models in order to integrate multi-system measurements [29–34].

The deployment of multiple constellation satellites and the development of modernised signals has now made it possible to obtain rapid and precise positioning information, not only for high-grade geodetic receivers, but also for handheld low-cost receivers, or even smartphones [35, 36]. Low-cost GNSS hardware comprises chipsets routinely used in smart devices produced e.g. by Broadcom, Qualcomm or Intel, whereas higher-performance hardware is employed in devices from e.g. SkyTraQ and u-blox [37–40]. The latter claim to ensure higher accuracy and reliability of positioning data, whereas the former are commonly used in mass-market devices for a number of location-based services such as personal and vehicle navigation and tracking, social networking, geocoding, etc., where an accuracy level of several metres suffices [2, 4, 41, 42]. According to GNSS market reports, smartphones now the dominant installation base for GNSS devices [43]. In response to market demands, the theory and algorithms of smartphone positioning have become one of the more frequently investigated and disputed topics in the field of GNSS. This progress is driven by two main factors. The first is the recent noteworthy development in the performance of mass-market GNSS chipsets. Initially, with these devices, it was feasible to acquire single-frequency single-constellation signals. However, to address user demand for enhanced accuracy, manufacturers now provide multi-constellation dual-frequency chipsets capable of tracking modernized GNSS signals. A particular milestone was the launch in September 2017 the first dual frequency GNSS chipset by Broadcom; BCM47755 [44]. This development was emulated by other producers such as U-blox, STMicroelectronics, and Qualcomm, who also introduced multi-frequency multi-constellation chipsets: namely F9, Teseo, and Snapdragon X24 LTE [45–47].

The second factor which brought smartphone positioning to the attention of the scientific community was the capacity to make raw observations retrieved from the GNSS chipsets in smart-devices available to both users and developers [48]. As a result, not only code pseudorange but also carrier phase and Doppler GNSS measurements are now accessible through Application Programming Interface 24 on devices running on the Android Nougat 7 operating system. The availability of such smartphone-derived GNSS measurements has given rise to a number of studies on signal quality, algorithm development aimed at enhancing the positioning accuracy of mass-market devices, and applications.
This article reviews the current knowledge in the domain of smartphone GNSS positioning and applications. The objectives are to acknowledge the most important and recent contributions to the field, and to identify prospective developments. This paper is organised as follows. Section 2 presents a review of recent studies relating to smartphone observation assessment. Section 3 acknowledges research papers devoted to the evaluation of positioning performance as well as the development of dedicated algorithms to handle smartphone observables. Section 4 presents and discusses advances in the application of such receivers. Section 5 concludes the study and outlines potential further progress.

2. Characterization of smartphone GNSS observations

Atmospheric delays are a major contributor to the quota of errors in positioning and applications using high-grade GNSS receivers. Specifically, ionospheric and tropospheric refractions are responsible for over half of the total of errors; however, this ratio strictly depends on processing methodology as well as the state of the atmosphere. This assumption also holds true for low-cost receivers. However, it is recognized that in the case of smart-devices, receiver-dependent errors are also a significant factor in the deteriorating performance of GNSS positioning. In response to this, great efforts have been made to evaluate measurement noise, to assess the impact of multipath and low carrier-to-noise density ratios ($C/N_0$), and to investigate adverse phenomena present in smartphone-derived observables, such as a gradual accumulation of phase errors, the occurrence of small discontinuities and phase reflection as reported by Humphreys [49], and Riley et al [50], as well as duty cycling as a power-saving function employed by manufacturers [51].

2.1. Duty cycling handling

Duty cycling is a mode in which the GNSS chipset of the smart-device operates in a discontinuous manner, hence the hardware clock is active for only a fraction of each second, to support low power consumption and thus prevent battery drainage [52]. Such behaviour results in discontinuities in phase observables, making them almost unusable for the purposes of applications dependent on precise positioning methods, such as Precise Point Positioning (PPP) or Real-Time Kinematics (RTK). It is worth noting that duty cycling is only activated once the GNSS chipset acquires the ephemeris data. Hence, typically during an initial, approximately 5 min period, phase observables are not subject to this effect [53]. More recently, researchers have found that duty cycling switches off when the smartphone is in motion, and switches on during static sessions [54]. We should note that the Google/HTC Nexus 9 tablet was the first smart-device capable of collecting continuous GNSS phase observations. As a result, several researchers performed their studies using this device. Among the more significant contributions are those of Realini et al [55] who demonstrated the feasibility of precise close range relative positioning using a Nexus 9 tablet, Zhang et al [56], Håkansson [57], who characterised these observations, and Gim and Park [58] who evaluated the pseudorange positioning. Fortunately, with the latest Android version (P) it is possible to switch off duty cycling mode. Thus most recent smartphones are not subject to this adverse effect, rendering their observables suitable for processing. This is sure to encourage progress in terms of the future application of smartphone observations to phase-based positioning methods.
2.2. Strength of smartphone observations and impact of GNSS antenna

Researchers have paid particular attention to the analysis of $C/N_0$ of signals tracked by smart-devices. $C/N_0$, which is the ratio of the power of the signal carrier to the power of the noise in a 1 Hz bandwidth (dB-Hz) which, among other factors, critically depends on the receiver and the antenna [59]. Detailed studies on this topic revealed a low elevation-dependency and the presence of azimuthal asymmetry of $C/N_0$ in the case of smartphone-derived GNSS signals. This is likely to be related to the significant impact of the multipath effect on such observations [49, 57, 60, 61]. Moreover, researchers have reported significantly lower values of $C/N_0$ in smartphones, as compared to corresponding signals collected by high-grade receivers. The difference may be as much as 10 dB-Hz [62, 63]. In response to this, investigations have been conducted into the optimal weighting scheme of smartphone observations. The results indicate that the $C/N_0$-dependent observation weighting scheme is superior to the elevation dependent model in smartphone GNSS positioning [54, 64].

It is agreed that smartphone GNSS antennas are subject to low gain and poor multipath suppression [65]. Despite these constraints, Pesyna et al [66] proved, for the first time, the feasibility of centimetre-level precision positioning using a smartphone-quality GNSS antenna. The limitations of embedded antennas may be addressed by the application of an external one as shown in [50]. In this context, Li and Geng [67] recently demonstrated that, using a survey-grade GNSS antenna, the error of pseudorange single point positioning drops from approximately 10–20 m to a level of 5–8 m. Nevertheless, precise phase-based positioning using smartphone-quality antennas requires the information of the phase center offset and variations. This prompted a recent work by Nethonglang et al [68], which aimed to determine the phase centre of the Xiaomi Mi8 embedded GNSS antenna. This study was followed by that of Wanninger and Heßelbarth [69], who performed phase center calibration for the Huawei P30. This required ambiguity fixing and succeeded only for GPS L1 signals.

2.3. Observation noise assessment

Any comprehensive GNSS data quality check should evaluate observational noise. The results of such analysis contribute a great deal to the stochastic model. This is particularly important in relation to smartphone GNSS observations, since the noise of such measurements may extends over a dozen meters due to a high level of contamination by the multipath. Therefore this subject has been frequently investigated in recent years, and has revealed significant differences in the level of observation noise between smartphones and high-grade receivers.

Information on the quality of code pseudoranges may easily be obtained from the differences between code and carrier phase measurements. Such a combination was applied by Lachapelle et al [70], the results of which showed an RMS value of of over 2.2 m RMS for a Huawei P10 smartphone, approximately ten times greater than that of a high-grade receiver. A comparable ratio between the code noise of a Nexus 9 smartphone and a high-grade receiver was obtained by Li and Geng [67], who used a third-derivative approach. In the case of phase observations, the smartphone measurement noise was only 3–5 times larger compared to high grade receivers reaching up to 0.04 cycles.

Time series of DD observations for zero baselines are also commonly employed for the evaluation of observation noise in high-grade receivers. However, this is rarely possible for smartphones owing to their lack of an external antenna connector. Therefore, an ultra-short baseline scenario may be used as a substitute. The results of such investigations confirmed a noise level of phase and code observations for a Huawei P20 several times higher than that of a high grade receiver [64]. In this context Liu et al [54] employed single differences between a
high-grade receiver and a smartphone and reported significant differences between the code noise of signals from different constellations. A detailed analysis of the GNSS observational noise of recent models of smartphone was also presented by Wanninger and Heßelbarth [69]. The authors employed i.a. multipath combination [71], taking advantage of the dual-frequency observations of a Huawei P30. The results showed the low-elevation dependence of the multipath combination, and confirmed a noise level of code observations one order of magnitude larger than that of high-grade receivers.

3. Precise positioning and navigation with smartphone GNSS observations

3.1. Performance assessment of positioning with smartphone GNSS observations

In addressing the demands of science and industry, a great deal of effort has been made to evaluate the accuracy which may be reached with current smartphone GNSS chipsets, and to identify potential areas of research to promote solution enhancement [72–77]. Some preliminary studies on smartphone GNSS positioning investigated the improvement which may be achieved in the urban canyon environment. In [78] the authors took advantage of the shadow-matching algorithm [79] and presented for the first time a comprehensive performance assessment of absolute smartphone GNSS positioning based on this technique. The benefit of the integration of 3D map-aided GNSS with smartphone-based pedestrian dead reckoning in such a challenging environment was also shown by Hsu et al [41]. A more recent study not only highlighted obstacles such as duty cycling mode present in low-power consumption smartphones and characteristic of embedded antennas, but also demonstrated a potential approach to providing a precise position [35]. One of the earliest performance assessments of smartphone single point positioning was contributed by Sikirica et al [80]. The authors evaluated pseudorange positioning with a Huawei P10, and reported an accuracy level of approximately 10 m and 20 m for horizontal and vertical components, respectively. Obviously, such values cannot be considered as highly precise. Similar conclusions were also reached by Specht et al [42], and Szot et al [81], who evaluated kinematic, and static single point positioning, respectively. Following these studies, Odolinski and Teunissen [38] recently assessed smartphone multi-constellation single-frequency precise positioning in RTK mode for various ionospheric disturbance periods, and determined the accuracy level which may be achieved under such conditions. Lachapelle and Gratton [82] investigated the performance of static PPP with the current class of smartphones, and showed much improvement with respect to the results pertaining to previous models of smart devices. The authors demonstrated that it is now achievable to obtain a coordinate accuracy in the order of 1 m after 30 min of data collection.

3.2. Progress in processing algorithms

Much progress has been made in terms of algorithms and strategies which address the features of smartphone GNSS observations. Currently, research is mostly directed towards the enhancement of positioning in relative and precise point positioning modes. An early study by Kirkko-Jaakkola et al [83] pointed to the possibility of improvement of positioning performance by means of a sparse permanent GNSS network and a relative mode. The authors achieved a horizontal accuracy no worse than 0.5 m, available for over 90% of the time using a u-blox low-cost receiver in a medium-range network RTK mode, but at the same time reported much less precise results obtained with the smartphone. Nonetheless this still required uninterrupted data transmission from the reference network. Yoon et al [84] validated a DGNSS coordinate projection method for smartphone positioning. The method, which is the development version of position-domain
differential GNSS positioning, addressed past limitations such as the unavailability of raw GNSS observations. The authors proved that using this method it is possible to improve positional accuracy by approximately 30%–60%, and eventually to achieve a 1 m level of accuracy. On the other hand, in regard to the current availability of raw smartphone observations, a range-domain correction model is recommended and considered as superior to a position-domain approach. Pesyna et al [85] investigated the issue of poor multipath suppression in low-cost GNSS antennas, resulting in a deterioration of the time-to-fix in precise relative positioning. The authors demonstrated that a substantial improvement may be obtained from a gentle wavelength-scale random antenna motion. Zhang et al [56] validated an approach based on established GNSS measurements time-differencing [86] to address the low quality of smartphone observations. The time-differenced carrier phase technique employs single-differenced observations and compares the difference between phase observations of consecutive epochs. The results showed that it is possible to obtain a positional error of less than 0.6 m and 1.4 m for horizontal and vertical components, respectively. As a natural consequence of time differencing, such a solution does not account for ambiguity resolution. Addressing the limitations of phase observations hampered by duty cycling, Paziewski et al [64] examined code-based long-range relative positioning, and reported a clear benefit from the C/N0-dependent weighting scheme in terms of coordinate accuracy. More recently, Gogoi et al [87] evaluated collaborative Android smartphone positioning to enhance positioning performance. The technique takes advantage of sharing raw observables between smartphones to retrieve a range between the devices. Zhang et al [88] presented an enhanced algorithm of RTK positioning using smartphone observables. The method uses a Doppler-Smoothed-Code filter and constant acceleration to reduce the measurement noise of code pseudoranges and to predict the kinematic state of the smartphone, respectively. As a result the authors reported achieving positioning accuracy to several decimeters. Dabove and Di Pietra [89] aimed to apply medium-range network RTK to smartphone GNSS data. The authors compared the results obtained with Samsung Galaxy S8 + and Huawei P10 plus smartphones to those obtained with a u-blox EVK-M8T low-cost receiver. The results showed that it is feasible to specify smartphone position with an accuracy of less than 1 m.

In spite of this remarkable progress, one of the major limitations preventing the achievement of centimetre-level accuracy using smartphone GNSS positioning is the presence of unaligned chipset initial phase biases (IPBs) [90]. To overcome this constraint, Geng and Li [91] calibrated the IPBs in a post-processing mode, which allowed for ambiguity resolution and, as a result, provided a precise centimetre-level position in a relative mode, and an improvement of up to 80% as compared to the float solution. In addition, several studies relating to PPP with smartphone observations have also been conducted. This area is covered in a paper by Banville et al [92]. Although still limited in application, PPP may provide a precise solution to cm-level, based on single-frequency observations, and with the support of external ionospheric corrections derived from a regional network of GNSS stations.

3.3. Benefits from dual-frequency observations provided by recent GNSS chipsets

Within the scientific community, much attention has been paid to the first smartphone equipped with a dual-frequency GNSS chipset; i.e. the Xiaomi Mi8 [44, 93, 94]. Such specifications ionospheric delays to be managed, e.g. by means of ionosphere-free linear combination or slant ionospheric delay estimation [95]. In this context, Warnant et al [61] demonstrated ultra-short baseline relative positioning, achieving centimetre-level precision for horizontal and decimetre-level precision for vertical components, respectively. One of the early
studies in this field was conducted by Robustelli and Pugliano [22]. The authors not only assessed the observables but also analysed static relative positioning, achieving approximately meter-level accuracy, taking advantage of the absence of the duty cycling mode. A subsequent contribution from Chen et al [96] investigated the performance of PPP with a Xiaomi Mi8 smartphone. The authors demonstrated the divergence between phase and code pseudorange observables, necessitating the estimation of two receiver clock corrections corresponding to a particular measurement type. With the application of the developed model, the authors achieved a positioning accuracy of 0.8 m and 1.6 m for horizontal and vertical components, respectively. Continuing this research using a Xiaomi Mi8 smartphone, Nethonglang et al [68] concluded that the smartphone may offer positioning data to a centimetre-level of accuracy, provided that the phase center offset of the embedded antenna is known. A study conducted by Aggrey et al [97] looked at the performance of PPP using raw observations from recently released smartphones, namely the Xiaomi Mi8, the Google Pixel 3, the Huawei Mate 20, and the Samsung Galaxy S9. Their analysis aimed to establish the accuracy level that might be achieved by such devices. The results demonstrated that an average horizontal error of 0.6 m and 0.4 m may be obtained for single and dual frequency PPP, respectively. Detailed results demonstrated that it was possible to obtain a decimetre-level accuracy in a 38-min convergence time. More recently, Wen et al [98] performed, for the first time, PPP with integer ambiguity resolution, using observations from a Xiaomi Mi8 smartphone, and achieved a centimetre-level accuracy of position. In order to accomplish this, the authors replaced the embedded GNSS antenna with an external geodetic-grade antenna.

4. Applications for smartphone GNSS observations in novel areas of science, industry and the mass-market

One of the natural fields of application for smartphone-based positioning is low-cost mobile mapping systems. As initial studies have shown, smart-devices may be effectively employed in such applications, as well as in cases of GNSS unavailability or under conditions where terrain is obstructed [99–101]. In this context, Alsubaie et al [102] demonstrated a novel approach, based on relative orientation and motion sensor measurements, in order to improve the accuracy of mobile mapping using smart-devices. However, in view of recent progress in the algorithms of smartphone GNSS positioning, it is believed that such applications may be more precisely realized by taking advantage of GNSS measurements [103]. This was demonstrated by de Frutos and Castro [104] who used smartphones as a low-cost tool for road inventories. Their results illustrate the effectiveness of smartphones in such applications. Subsequent studies conducted by Lee et al [105] proved the feasibility of using smart-devices to monitor road-geometry, and for crash-risk estimation. A clear benefit of the fusion of navigation sensors was demonstrated by Gikas and Perakis [106], who evaluated the application of smartphone GNSS, integrated with IMU, to Intelligent Transportation System services. The advantages of integrating smartphone GNSS signals with other navigation sensors have also been examined in recent studies by Li et al [107], Sheta et al [108], Yan et al [109], and Mostafa et al [110], among others.

More recent studies demonstrate the application of smartphone sensors in more challenging fields such as geoscience, and geohazard studies. Kong et al [111] demonstrated that a dense network of smartphones equipped with accelerometers may be used to develop an early warning system for the detection of earthquakes. Moreover, information collected in this way could also be used to provide microseismic maps, and to support structural health monitoring systems. Following on from this, Fortunato et al [112] performed a feasibility study based
on the application of smartphone GNSS observables to selected geoscience real-time applications, specifically the monitoring of seismic events and ionospheric disturbances. The authors proved that previously developed VADASE and VARION algorithms [113, 114] fed with low-cost receiver observations had the potential to constitute a base for geohazard monitoring systems. An encouraging novel application of smartphone GNSS observations in the field of geoscience was also demonstrated by Tagliaferro et al [115]. The authors performed a feasibility study on the potential of retrieving information on the troposphere using mass-market smart devices. Since the presence of water vapour may easily be deduced based on zenith tropospheric delays, which are estimated in GNSS processing, the resulting data may be incorporated into Numerical Weather Prediction models in order to supplement weather forecasting [116]. It is worth noting that mass-market devices may significantly increase the spatial resolution of observations. The results provided by Tagliaferro et al [115] demonstrated a high degree of agreement between smartphone- and high-grade receiver-derived tropospheric delays. In the light of this recent progress, it is anticipated that the number of potential applications for mass-market devices may eventually outnumber those for which high-grade receivers are required.

5. Conclusions and outlook

Despite the above advances, there are still many limitations restricting the use of smartphones for highly precise position-based applications. These limitations include the low quality of current embedded antennas expressed as a high susceptibility to multipath, and low gain and linear polarization, which precludes the differentiation of right-hand circularly polarized direct line-of-sight signals from reflected left-hand circularly polarized non-line-of-sight signals. Another issue is the lack of phase centre offset and variation models for the majority of smartphone GNSS antennas. Future research should also address the significant problem of the integer ambiguity resolution of smartphone phase observations in real-time. Taking advantage of the multiple sensors with which smart-devices are equipped, enhanced positioning methods should focus on the fusion of these with GNSS chipsets. Nonetheless, based on recent advances, it can be assumed that the current rate of progress in smartphone GNSS receiver architecture, algorithms and applications will continue. Furthermore, the presumption of low-performance commonly related to low-cost receivers may not hold true in the near future, since such receivers may potentially achieve a performance level close to that of high-grade receivers which would open the door to further novel applications.

Acknowledgments

The work in this contribution was supported by the National Science Centre, Poland: project No. 2016/23/D/ST10/01546.

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