GNSS Kinematic Positioning Test Using Modified Signals Received by Smartphones

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ABSTRACT

Some mobile devices with an Android operating system have already acquired and recorded the GNSS satellite's dual-frequency carrier phase. If this type of smartphone can achieve high-precision GNSS kinematic positioning, the cost of devices will be effectively reduced. It is, then, expected to meet the standard of 20 cm positioning error required in pipeline surveying works. A smartphone of Mi8 was used in this study as a front-end data receiving tool, and the PPK positioning was carried out for a complete check on its operability, accuracy, and modification. The study found that the Mi8 smartphone could not effectively conduct moving observation, the broadcast ephemeris was not useful in data processing, and the positioning performance was unstable during different periods in a day. Importantly, the GNSS modified signal produced by the geodetic antenna and re-radiating kit with sheltering operation is proved to be effective. Its average positioning error could be better than 16 cm, through which it could decrease the error by at least 30% compared to the original signal.

Keywords: Global Navigation Satellite System (GNSS), Post-Processing Kinematic (PPK), smartphone, re-radiating kit, modified signal

智慧型手機接收改良信號之 GNSS 動態定位測試

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摘　　要

Android 系統的部分行動設備，已可進行 GNSS 衛星雙頻載波相位觀測量之獲取與紀錄。此類型之手機，若可達成高精度 GNSS 動態定位解算，將可有效降低作業裝置之成本，亦可滿足管線圖資更新測量之 20 公分定位誤差標準。本研究主要使用 Mi8 智慧型手機為資料接收工具，並採後處理動態定位模式進行解算，以進行其操作性、精確性及改良性之完整檢核。經測試可知，Mi8 相位觀測量並不適用於移動式定位，也不宜使用廣播星曆進行解算，另在同天不同時段之定位表現也不穩定。本研究提出 GNSS 大地型天線配搭信號轉發套件及遮罩方式所接收之改良信號，其平均誤差可優於 16 公分，且可較原始信號之誤差至少降低 30%。

關鍵詞：全球導航衛星系統、後處理動態定位、智慧型手機、信號轉發套件、改良信號

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Ⅰ. INTRODUCTION

Each modern smartphone has an embedded GNSS receiver chip. However, the GNSS raw data were not available to users at early beginning because they were protected by the chip manufacturers. This problem finally got a breakthrough in May 2016, when Google announced its Android Nougat (or version 7) operating system at the annual developer conference. This system can provide raw data of GNSS through Apps.

Subsequently, through the application programming interface (API) of the Android operating system, smartphones with such mobile platforms can directly acquire and store GNSS raw data. This capability made it possible for smartphones to conveniently carry out precise positioning. In addition, smartphones can combine accelerometers, gyroscopes, electronic compasses, cameras, barometers, and other sensors, allowing many application services in the field of geolocation [1].

When using the mobile positioning services of smartphones, the decimeter-level positioning applications can involve parking, logistics, shared transportation, emergency rescue, automatic driving, and other operations in smart cities. It is even more common in application projects such as location-based services (LBS), vehicle navigation, road monitoring, and mobile mapping [2].

Furthermore, in the development history of smartphones, early Android devices, such as Google/hTC Nexus 9, had a duty cycle problem as low power consumption GNSS chips were used. This problem caused each GNSS phase observables received by smartphones to have cycle slips, making it difficult to solve high-precision kinematic positioning [3].

During the 2016-2018 testing phase, Banville & Van Diggelen [4] used the tool of GNSS Logger released by the Android team to collect three minutes of GPS single-frequency data. They found that the carrier-to-noise density ratio (C/N_0) of the signal received by the smartphone antenna was easily affected by how the smartphone was held. In addition, as the smartphone antennas were mostly designed with linear polarization, the smartphone easily received the GNSS signal reflected from the ground or the adjacent surface. Hence, it was easy to have the multipath effect. Moreover, it was likely to cause high noise and possible bias because the smartphone must be able to distinguish between direct and reflected signals during signal processing. At this time, the C/N_0 of the GNSS signal received by the smartphone antenna may have been reduced by about 10 dB-Hz compared with the geodetic antenna used for observation.

In addition, Riley et al. [3] used two smartphones, Nexus 9 and Samsung S7, for testing. They found that the GPS satellite signal may still fade in an open environment, and they judged that it should be caused by the multipath effect. In addition, the C/N_0 of a certain smartphone was low, which often stopped the positioning. However, when the smartphone received signals with an external GNSS geodetic antenna, its positioning results could be improved.

Similarly, in Odolinski and Teunissen [5], it was found that under the conditions of low ionosphere activity, if a smartphone was connected to a geodetic antenna for reception, the ambiguity resolution of phase observables could be successful in real-time. The position accuracy could then be achieved at the centimeter level.

During the evolution of smartphones, Xiaomi Mi8, a product with a new specification, was officially announced on May 31, 2018. It was the world's first smartphone capable of providing GNSS dual-frequency carrier phase. The smartphone Mi8 was embedded with a Broadcom BCM47755 chip, which can cooperate with the smartphone's receiving and processing software, the GNSS API of the Android operating system, and the installed GNSS data logging Apps, to form the GNSS dual-frequency carrier phase receiving system for the smartphone [3]. The types of GNSS signals that this smartphone can receive include GPS L1/L5, GLONASS L1, BeiDou B1, Galileo E1/E5a, and QZSS L1/L5 [6].

In his comment in the article written by Haddrell et al. [7], Professor Langley mentioned that the antenna is the most important factor for good GNSS signal reception. Since GNSS signals are right hand circularly polarized, the corresponding polarization matched receiving antenna can still transmit the maximum signal power to the receiver, despite the satellite direction changing during the signal transmission. However, as the smartphone must not only provide voice communication but also need to connect with headphones, Wi-Fi, or Bluetooth, and must be small and affordable, this limitation will move GNSS antennas towards miniaturization and combination. Moreover, it also leads to a significant reduction in the signal gain, which is the inherent limitation to the smartphone's GNSS antenna.

With Android smartphones receiving GNSS raw data, researchers can use the GNSS carrier phase observables for related applications at a precise positioning level. However, there is an obvious limitation; that is, no smartphone manufacturer has officially disclosed the position of the antenna phase center embedded in its smartphone. The phase center position of the GNSS antenna required for high-precision satellite positioning should be discussed as a priority so that the GNSS receiving point of the smartphone can precisely correspond to the ground measuring point. In this regard, Netthonglang et al. [8] established that the antenna phase center of the Mi8 was at the upper left of the front of the phone. In other words, it was 2.8 cm to the left from the center of the upper edge of the smartphone and 0.9 cm away from the upper edge. This definition was applied to the present study when performing the subsequent centering of the smartphone.

In applying the precise positioning using the GNSS phase observables received by smartphones, the application object in this study was based on the surveying works after the underground pipeline was buried. Although the GNSS real-time kinematic (RTK) positioning was mainly used in the field operation, the quality of the observation based on the smartphone has not been clarified in the study. Hence, this study adopted the Post-Processing Kinematic (PPK) mode for smartphone-based GNSS positioning. The target accuracy was based on the 20 cm required for manhole cover and pipeline positioning as the national standard.

Therefore, this study used a smartphone capable of providing GNSS phase observables as the front-end data receiving tool for PPK positioning. In addition, a complete investigation of the error of positioning results was conducted through related test procedures, such as the signal quality inspection, zero-baseline calibration, different ephemeris utilization, moving and fixed observation, multi-session positioning, and modified signal improvement. By doing so, the operability, accuracy, and improvement of the application ability of smartphones in GNSS high-precision positioning could be clearly understood.

The research architecture is shown in Fig. 1.

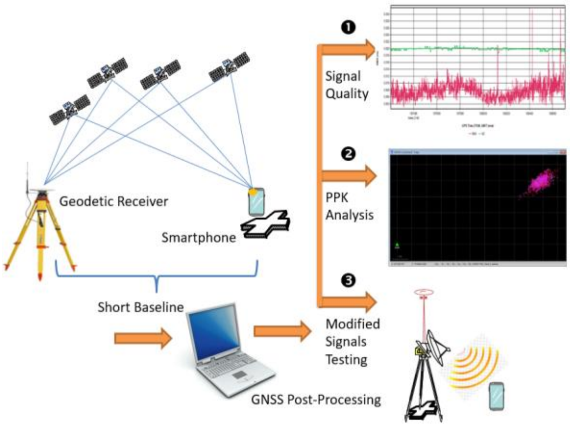


Fig. 1. The operational architecture of this study

Ⅱ. TESTS OF ORIGINAL SIGNAL

According to the literature, difficulties in GNSS observation for Mi8-type smartphones may occur because of the unstable signal reception and multipath effect mainly related to poor antenna quality [9-10]. To fully understand the performance of smartphone-based GNSS phase observables for precise positioning, a short baseline of about 55 m in length was used in this study. A NovAtel ProPak6 (PP6) geodetic GNSS receiver was used for the base station of the baseline, while a smartphone receiver was used for the rover.

The baseline observation was recorded with one epoch per second. Then, the positioning was solved by the Waypoint GrafNav 8.90 in PPK mode [11]. The dual-frequency observations provided by smartphone receivers were L1/L5(E5) and the number of modernized satellites that can transmit the L5(E5) was still uncommon, so only single-frequency of L1 observables were used for the PPK solution in this study, which is believed to affect the short baseline positioning not significantly.

2.1 Evaluation Indicators

In this study, the internal precision and external accuracy of the positioning results were discussed in terms of the assessment of smartphone GNSS positioning solution obtained by the PPK mode. The use of each type of evaluation indicator is defined as follows:

(1) The standard deviation of the solution set

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(X_{PPK} - X_{mean})_i^2}{n-1}} \quad (1)$$

In Eq. (1), σ is defined as the standard deviation obtained after subtracting n epochs of PPK solutions (X_{PPK}) from the mean of the solutions (X_{mean}); the smaller the value of σ, the smaller the dispersion of the PPK results. In this study, this indicator was mostly used when the smartphone was observed at a fixed point, but not centering to the ground point so that there was no known coordinate for checking.

(2) The average standard deviation of the epoch solution

$$\overline{\sigma} = \frac{\sum_{i=1}^{n}\sigma_i}{n} \quad (2)$$

In Eq. (2), the calculation of $\overline{\sigma}$ is to average the standard deviation of each epoch solution (σ_i) with the solution number in the group (n); the smaller the value of $\overline{\sigma}$, the smaller the solving error. This indicator was mostly used in this study when the smartphone was used for moving observation. The value in Eq. (1) could not be obtained because the observation was not repeated at the same point, and there were no known coordinates at each moving point for checking.

(3) The root mean square error of the solution set

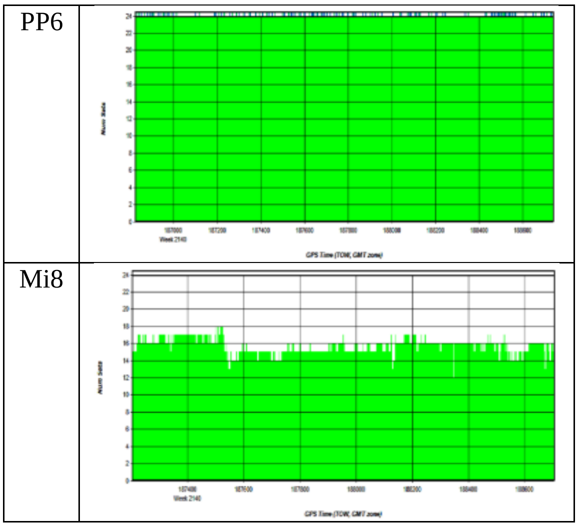
$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(X_{PPK} - X_{static})_i^2}{n}} \quad (3)$$

In Eq. (3), RMSE is the root mean square error obtained by subtracting the n epochs of PPK solution (X_{PPK}) from the known coordinates (e.g. X_{static} from GNSS static solutions); the smaller the RMSE value is, the smaller the difference between the PPK solution and the known value. This indicator was mostly used in this study when the smartphone was observed at a fixed point, and the point has higher accuracy of coordinate for checking.

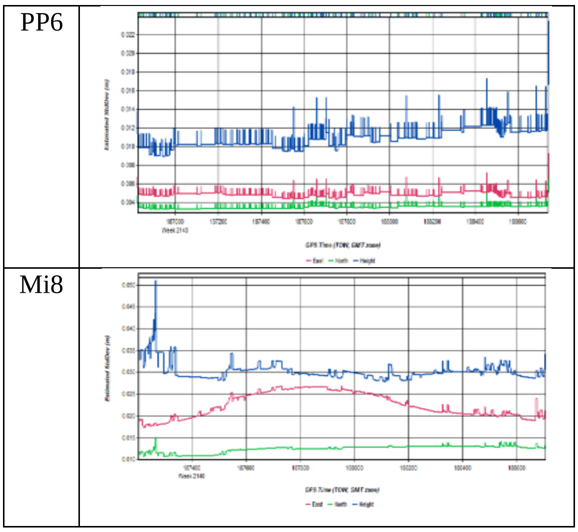
2.2 Signal Quality Comparison

In this study, a PP6 geodetic receiver and a Mi8 smartphone were set up at 12:00 local time on January 12, 2021 on the university building roof in Taoyuan, adjacent to each other, for 15 minutes (see Fig. 2). A comparison of the signal quality-related indicators of their performances is shown in Fig. 3.

Fig. 2. Simultaneous GNSS observations collected by PP6 and Mi8



(a)



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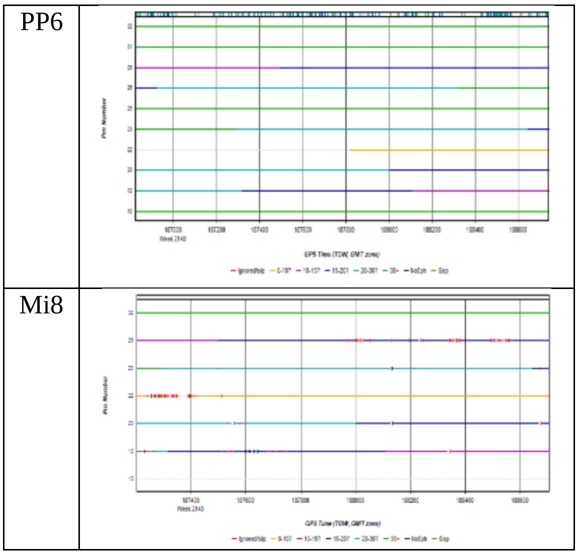

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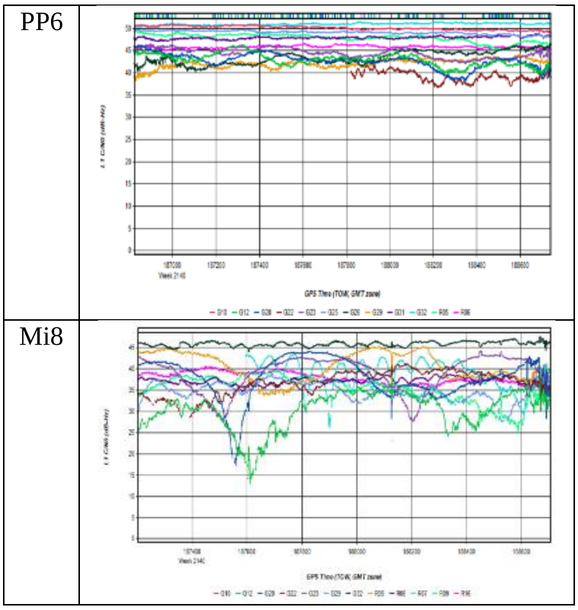


(d)

Fig. 3. Comparison of GNSS signal quality received by PP6 and Mi8 for: (a) number of satellites, (b) estimated position accuracy, (c) GPS L1 cycle slips, (d) L1 C/N0 for GPS and GLONASS

From the above-mentioned quality indicators reflected by the observations of the geodetic GNSS receiver (PP6) and the smartphone receiver (Mi8), it can be seen that the number of satellites received at the same time is about 24 for PP6 and about 16 for Mi8. In terms of PPK estimated positioning accuracy, PP6 is about 0.5 cm in the plane and 1.2 cm in height, while Mi8 is about 2.5 cm in the plane and 3 cm in height. For GPS L1 cycle slips, PP6 is almost absent, while Mi8 is frequent. In terms of L1 carrier/noise ratio (C/N$_0$), PP6 locates at 40-50 dB-Hz, while Mi8 is about 30-45 dB-Hz.

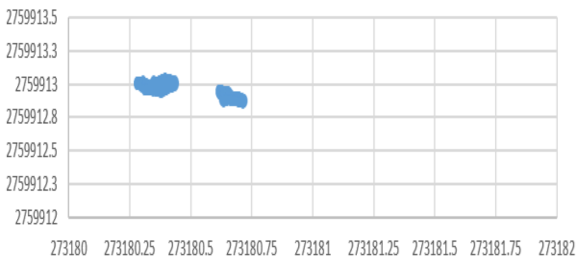
Ultimately, similar to the study of Robustelli et al. [2], the findings of the present study indicate that the GNSS signal quality of the smartphone receiver (Mi8) is indeed worse than that of the geodetic receiver (PP6).

2.3 Ephemeris Testing

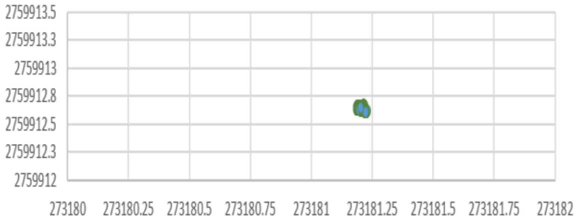
In understanding the difference in the performance of the PPK solution of smartphone observables with different levels of ephemeris, this study used broadcast ephemeris (BE) and precise ephemeris (PE) with two sets of Mi8 data collected at the same site in 2021 and 2022, respectively. Eq. (1) was used to compare the standard deviations of two solution sets (see Table 1), and the distribution of the plane coordinates of the second data set is shown in Figure 4.

Table 1. Positioning errors of PPK solutions using BE and PE

Data set (Date)	2D (cm)		H (cm)	
	BE	PE	BE	PE
2021/1/21	31.8	6.5	15.7	7.9
2022/1/11	15.2	1.5	23.0	6.1
Average	23.5	4.0	19.4	7.0



(a)



(b)

Fig. 4. Distribution of PPK plane coordinates for the second set of smartphone observations by using: (a) BE, (b) PE

As shown in Table 1, the positioning performance of PE is better than that of BE, and the average difference is about 20 cm in the plane component and 12 cm in the vertical component. In addition, the distribution of plane coordinates in Fig. 4 showed that in addition to the scattered differences, there were two concentrated blocks in the BE solution, and their coordinates deviated from the PE positioning results by up to 75 cm. Obviously, the results of the PE solution show much reliable performance.

2.4 Moving Testing

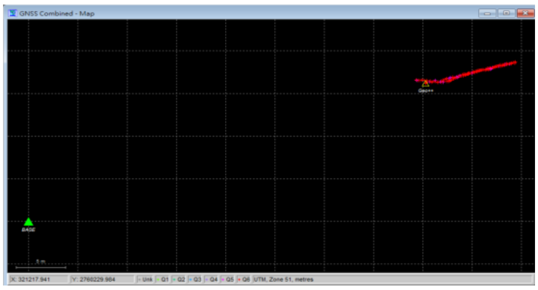
In an attempt to understand the positioning performance of the smartphone in a slow-moving state, this study collected two data sets with different moving routes (one straight line and one elliptical) with Mi8 smartphones on January 15, 2022. They were combined with the base station data of PP6 observations to perform a one-second epoch of PPK positioning using the precise ephemeris.

In exploring the performance, this study also included the solutions of the fixed-point observation and showed the comparisons in Table 2. It used Eq. (2) to calculate the average standard deviation of the epoch solution in each set of positioning solutions. The distribution of plane coordinates obtained by two sets of moving reception data is drawn in Fig. 5.

From the test results, it can be found that the positioning error of the Mi8 smartphone in the slow-moving condition is much worse than that of the fixed-point observation, and the difference can be up to 20 times or more, consistent with the findings of Dabove et al. [12], who suggested that the success rate of fixed ambiguity resolution of smartphone observables was significantly lower.

Table 2. Positioning errors of PPK solutions with different observation types

Observation	Route	2D (cm)	H (cm)
Stationary	Fixed point	1.3	2.2
Moving slowly	Straight line	35.9	41.6
	Elliptical	40.8	92.1



(a)

(b)

Fig. 5. Distribution of PPK plane coordinates observed by smartphone with: (a) straight line moving, (b) elliptical moving

2.5 Multi-session Testing

In an attempt to understand the positioning performance of smartphones during general operating hours, this experiment was conducted between 9:00 and 20:00 local time on March 27, 2021 using Mi8 smartphones to collect 15 minutes of fixed-point observations every hour. Then, it was combined with the base station data to perform a one-second PPK positioning solution using a precise ephemeris.

Because the smartphone was placed on the tablet, and the static observation was carried out after centering and leveling, it is possible to investigate the external accuracy of the PPK positioning results, based on Eq. (3). To determine the precise coordinates of the check point, two PP6 receivers were used for static observation and baseline solution. The root mean square errors (RMSEs) of each solution set group were obtained (see Table 3). The variation of the errors during an operating day is shown in Fig. 6.

The external accuracy shown in Table 3 indicates that the Mi8 positioning results are not good enough during the operating hours from daytime to evening, with an average plane error of 40 cm and a great variation between periods by up to 75 cm. Meanwhile, the error variation trend in Fig. 6 shows that there are two large peaks at

15:00 and 18:00, and 12:00, 16:00, and 19:00 are relatively better.

Table 3. RMSE of PPK positioning of smartphone observations at different time

Local time	N (cm)	E (cm)	2D (cm)	H (cm)
9	30.7	43.0	52.9	95.9
10	29.5	9.5	31.0	15.1
11	25.9	14.9	29.9	26.3
12	21.0	5.4	21.7	9.7
13	43.0	21.4	48.1	19.1
14	46.0	15.1	48.4	13.7
15	60.1	76.1	97.0	252.2
16	19.5	9.0	21.5	12.8
17	30.8	3.9	31.0	6.3
18	25.4	45.6	52.2	154.5
19	16.0	17.7	23.9	4.4
20	23.2	11.5	25.9	16.1
Min. value			21.7	4.4
Max. value			97.0	252.2
Mean			40.3	52.2

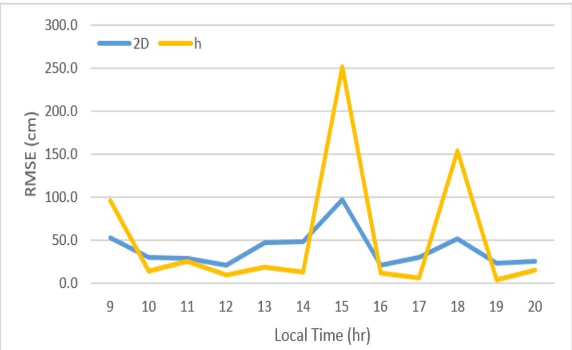


Fig. 6. RMSE of PPK positioning for multi-session observations

When further comparing the plane errors in a better period at 19:00 and a worse period at 15:00, as drawn in Fig. 7, the positioning error of the smartphone during the 15-minute observation period around 15:00 is unstable and may occur significant jumps during the observation period.

In the above-mentioned phenomenon, the external accuracy indicator (such as RMSE in Table 3) of the PPK positioning results based on smartphone observations showed a much larger value than the internal precision indicator (such as σ in Table 1). It may result from either the not-well-defined Mi8 antenna phase center or the ionospheric effect that causes abnormal satellite signals received by the smartphones [5][8]. Thus, in order to overcome the above dilemma of the large error occurred, this study proposed using the GNSS signal re-radiator to modify and improve the signal reception quality, and the details of which are as follows.

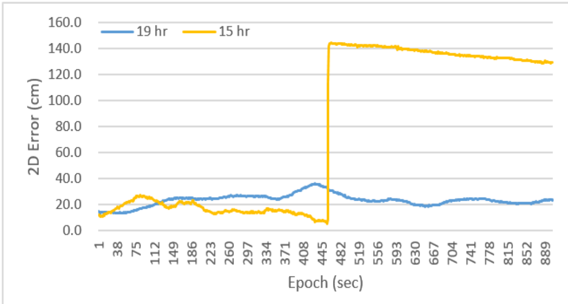


Fig. 7. Comparison of PPK plane errors observed at 15:00 and 19:00

III. TESTS OF MODIFIED SIGNAL

In improving the positioning accuracy of GNSS phase observables of smartphones, using an external antenna can be considered to enhance the quality of the received signals. Blot et al. [13] showed that the L1 code range could be improved, but the L1 carrier phase was not effectively improved, in which the signal noise was still three times higher than that of a typical geodetic receiver.

Since the above-mentioned improvement method has not been fully confirmed, and the PPK positioning mode has not been tested, this study proposed a combined device to provide the modified signal for smartphones' poor reception. Furthermore, this study further tested and discussed its operational effectiveness.

This modified GNSS signal transmission and receiving operation for smartphones was developed, as shown in Fig. 8. The modified signal generation device used a better quality and easy centering of GNSS geodetic antenna mounted on a pole for receiving the original satellite signal at the positioning point, and was equipped with a signal re-radiating kit consisting of AC power, filtering amplifier, and passive transmission antenna for operation (see Fig. 9).

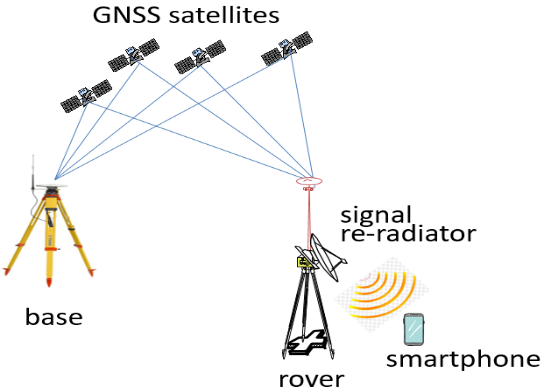


Fig. 8. Configuration and operation for smartphone receiving modified GNSS signal

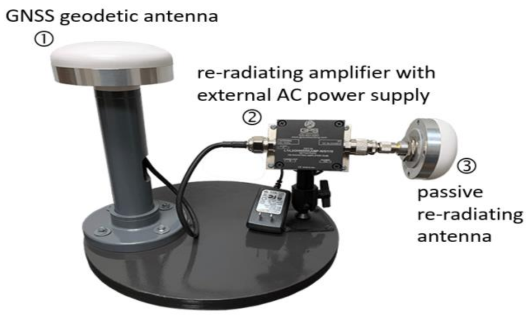
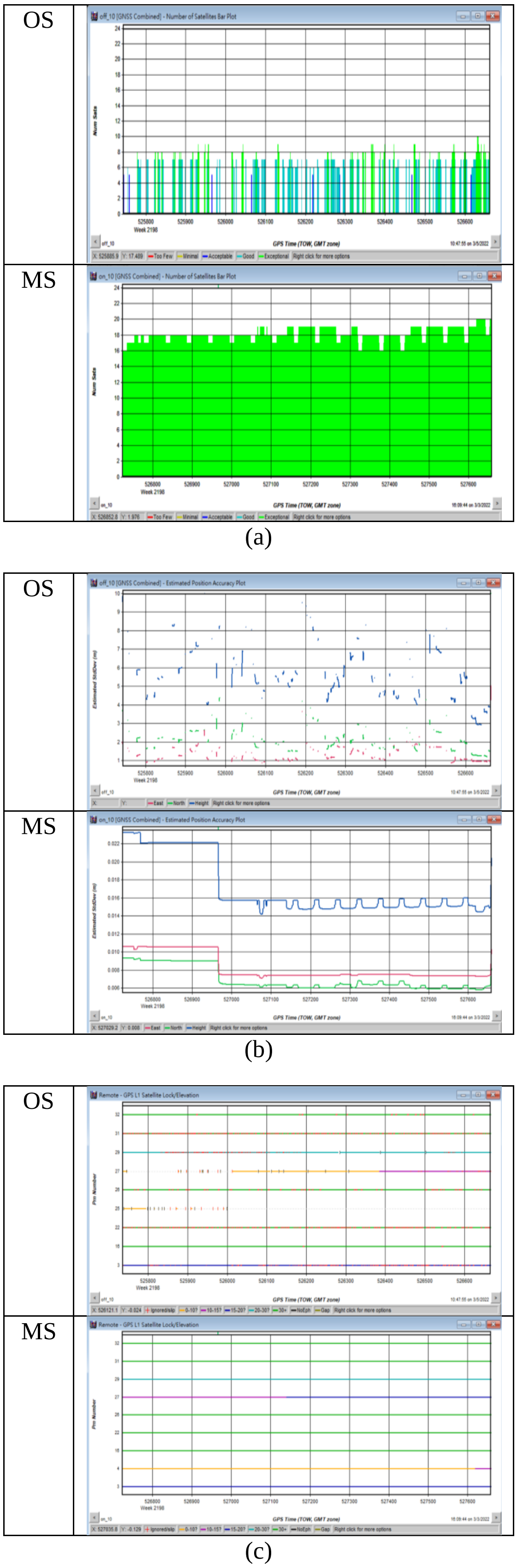


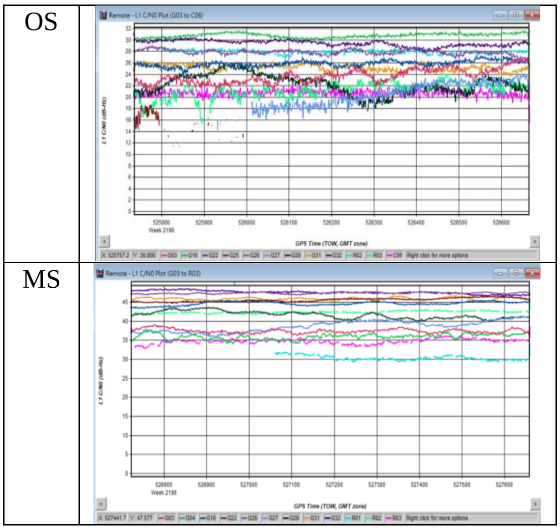
Fig. 9. Modified GNSS signal re-radiating kit

Under the operation of this design device, the GNSS observations can be recorded by a low-cost and lightweight smartphone. The positioning point was at the installation site of the geodetic antenna with the pole, which can avoid the centering problem caused by the uncertainty of the antenna phase center of the smartphone. This is because the GNSS signal has been filtered and transmitted by the re-radiating antenna, the observation quality and positioning performance of the modified signal received by the smartphone within an appropriate distance might be improved. These benefits will be practically tested and discussed in the following sessions.

3.1 Quality of Modified Signal

During the period of 10:00-11:00 local time on February 26, 2022, the Mi8 smartphone was used to receive the original and modified GNSS signals for 15 minutes on the top of a building on university campus. The evaluations of the received signal quality were compared and shown in Fig. 10.





(d)

Fig. 10. Comparison of the quality of the GNSS original signals (OS) and modified signals (MS) received by Mi8 for: (a) number of satellites, (b) estimated position accuracy, (c) GPS L1 cycle slips, (d) L1 C/N0 for GPS and GLONASS

As shown in the comparison in Fig. 10, it is clear that the quality indicators reflected by the original and modified GNSS signals received by Mi8 smartphones are significantly different. In terms of the number of satellites received in the adjacent period, the original signal has about 8 satellites, while the modified signal can reach 18 satellites. In terms of the PPK positioning accuracy, the original signal performs at the meter level, while the modified signal is within 2 cm. In the GPS L1 cycle slips occurrence, the original signal frequently appears, while the modified signal hardly appears. In the L1 carrier/noise ratio (C/N_0), the original signal value falls at 18-30 dB-Hz, while the modified signal is about 30-50 dB-Hz. For this test data, the quality of the modified signal received by Mi8 is indeed much better than the original signal and is comparable to the PP6 reception quality shown in Fig. 3.

3.2 Zero Baseline Testing

The zero baselines can be applied to determine the hardware internal error of GNSS receivers. This concept was also used in this study to understand the effectiveness of Modified GNSS signal received by smartphones. A GNSS geodetic antenna was set up on the outdoor roof, and the signal was transmitted to the indoor area using the re-radiating kit as Fig. 9. Since the indoor GNSS signal was relayed and modified from the original signal received by the roof antenna, the coordinates obtained by the indoor receivers should be the same. In terms of the baseline solution, the length of each baseline formed should be zero. However, a non-zero magnitude can be regarded as the positioning error caused by the GNSS receiver.

The test was conducted on December 6, 2021, at 11:00 am, using two PP6 geodetic receivers and one Mi8 smartphone for 40 minutes of data collection and performing a one-second interval of PPK positioning with the precise ephemeris. In this test, the Mi8 was not bothered by instrument centering, so Eq. (3) could be used to calculate the root-mean-square error of each baseline solution with zero length as the standard value. The comparison of the results is shown in Table 4. The error of each epoch solution for the PP6-PP6 baseline and the PP6-Mi8 baseline is shown in Fig. 11.

Table 4. RMSE of PPK positioning for zero baseline tests

Base	Rover	N (cm)	E (cm)	2D (cm)	H (cm)
PP6	PP6	0.7	0.2	0.7	0.1
	Mi8	1.0	0.3	1.0	1.0

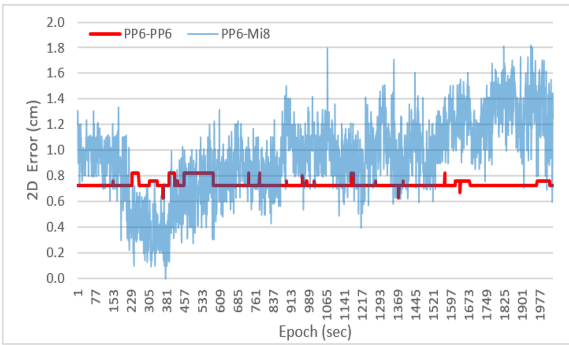


Fig. 11. Comparison of the zero baseline plane errors between PP6-PP6 and PP6-Mi8

The results of the zero baseline test listed in Table 4 were obtained under an observation environment with the modified GNSS signal. As expected, the better performance is found for the PP6-PP6 baseline of using two geodetic receivers, with a plane error of 0.7 cm. For the PP6-Mi8 baseline, which is the focus of this study, the plane error increases slightly to 1.0 cm when observed with one Mi8 smartphone. Compared to the internal precision and external accuracy obtained from the previous tests with the original GNSS signal, this level of Mi8 positioning error is a promising result. It is basically believed that the modified GNSS signal provided by this study's design device is capable of improving the Mi8's observation. However, when the positioning errors are examined in Fig. 11, it can be also seen that the stability of the Mi8's observation is still not as good as that of the PP6 geodetic receiver.

3.3 Outdoor Testing

In the previous zero baseline test, the modified GNSS signal transmitted into the indoor environment through the re-radiating kit was no coexistence between original and modified signals in the same space. To further check whether the coexistence of original and modified signals in the same open environment would have a near-far effect similar to that of pseudolite [14], the re-radiating kit was placed in the outdoor space to produce the coexistence between the original and modified GNSS signals in space.

This study was conducted at 12:30 local time on January 26, 2022, with a PP6 as the base station (receiving only the original signal) and a Mi8 set up at 3 m, 5 m, and 10 m from the re-radiating kit (see Fig. 12). The original and modified GNSS signals were received for 15 minutes each by turning the re-radiating kit on and off. The results are listed in Table 5.

As shown in Table 5, the Mi8 observations were not successfully solved at the baseline distance of 3 m and 5 m from the re-radiating antenna when the kit was turned on. Meanwhile, the standard deviation of the 2D solution set at a 10-m distance was much higher than that of the original signal received by Mi8.

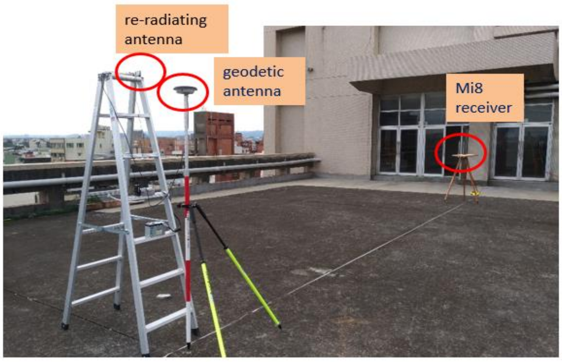


Fig. 12. Original and modified GNSS signals coexistence for outdoor testing

Table 5. Positioning errors of PPK solutions with re-radiating on or off

Baseline distance	Turing off (original signal)		Turing on (coexisted signal)	
	2D (cm)	H (cm)	2D (cm)	H (cm)
3 m	1.5	6.1	N/A	N/A
5 m	13.4	7.6	N/A	N/A
10 m	15.6	35.0	58.9	24.0

In addition, when the modified GNSS signal and the original signal coexist in the outdoor environment, the L1 phase observable cannot be effectively received at 3-m and 5-m distance from the re-radiating antenna, whereas the L5 signal which is believed to be more resistant to interference can be received. However, the satellites received in L5 is still insufficient and can only be an auxiliary observation in the GNSS processing software, thus, those solutions cannot be completed. Although the L1 phase observable can be received at a distance of 10 m from the re-radiating antenna, the positioning error is found to be large due to the possible interference effect between the original and modified signals.

3.4 Multi-session Testing with Sheltering

The near-far effect may occur when the original and modified GNSS signals coexist in the same outdoor space. Thus, this study proposed an operational improvement by placing the re-radiating antenna and Mi8 receiver to a space with sheltering (see Fig. 13). This shield is expected to block the original GNSS signal already existing in the open space. Meanwhile, only the modified GNSS signal from a re-radiating kit will be provided inside the shield.

Fig. 13. Outdoor smartphone observation with a shelter

Since the results of the previous multi-session test in Section 2.5 showed that the external accuracy of Mi8 observations was very unstable, this study adopted a re-radiating kit with a shelter to receive the modified signal only, expected to avoid smartphone centering problem and improve the stability of smartphone positioning at different time.

To carry out a complete test for the above purpose, a fixed point observation was made between 9:00 and 19:00 local time on February 26, 2022. The Mi8 smartphone was used to receive the original GNSS signal in the first 15 minutes of each hour and the modified GNSS signal with sheltering in the following 15 minutes. In addition, after combining with the base station data of PP6 observation, a one-second rate of PPK solution was performed using a precise ephemeris. The RMSEs of the two sets of the solution compared with the known coordinate of the test point are listed in Table 6, in which the improvement rates (IR) are also provided using the calculation of $(RMSE_{OS}-RMSE_{MS}) / RMSE_{OS}$ x 100%. The variations in the plane errors based on the original and modified signals in each session are plotted in Fig. 14.

Table 6. RMSE and improvement rate (IR) of PPK positioning with original signal (OS) and modified signal (MS) at different local time (LT)

LT	2D RMSE			H RMSE		
	OS (cm)	MS (cm)	IR (%)	OS (cm)	MS (cm)	IR (%)
9	519.7	3.8	99	1053.8	1.3	100
10	263.9	0.8	100	660.4	1.8	100
11	281.9	22.2	92	718.2	12.8	98
12	289.3	20.3	93	253.2	15.7	94
13	84.4	8.4	90	69.3	2.9	96
14	52.1	34.8	33	137.8	6.7	95
15	24.7	9.5	62	44.2	5.0	89
16	159.5	22.9	86	60.4	16.2	73
17	39.5	14.7	63	102.9	5.1	95
18	63.7	19.3	70	126.7	9.2	93
19	72.6	15.9	78	109.2	15.0	86
Avg	168.3	15.7	91	303.3	8.3	97

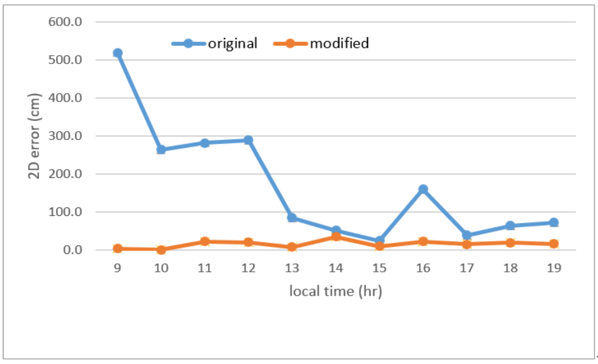


Fig. 14. Comparison of multi-session PPK plane error with different signals

From the external accuracy shown in Table 6 and Fig. 14, it can be seen that the results of PPK positioning with Mi8 observations can reduce the positioning errors by at least 30% during the operation hours from daytime to evening when the modified GNSS signal is received with sheltering. Besides, for the average improvement rate of more than 90%, the modified GNSS signal obtained with sheltering can reduce the average plane errors from 168 cm to 16 cm, and it can also low down the average vertical error from 303 cm to 8 cm.

Moreover, when looking at the detailed performance, it could be seen that the error in height could meet the requirement of 20 cm for pipeline positioning in all sessions when the modified GNSS signal was used. However, the plane error of larger than 20 cm still occurred in four sessions, e.g. 11h, 12h, 14h, and 16h.

Furthermore, for the two representative periods (15h and 19h) shown in Fig. 7, the variations of the plane errors using different signals in this test were also plotted in Fig. 15.

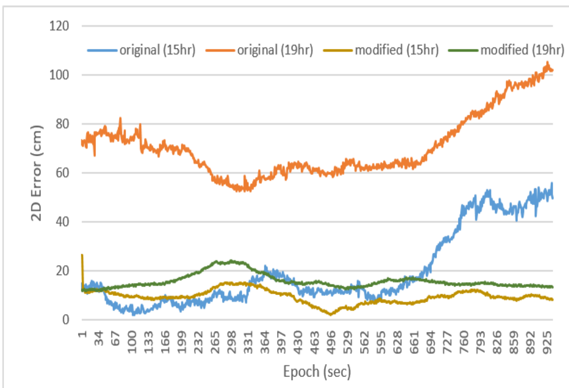


Fig. 15. Comparison of the plane error using different signals at 15:00 and 19:00

Compared with the original signal positioning error jump in Fig. 7, it did not occur in Fig. 15 of this test, and the modified signal positioning results with the sheltering reception were generally better and more stable than the original signal positioning. Observing the test results of near one year ago (March 2021 in Table 3), it can be seen that the average plane error has increased significantly from 40 cm to 168 cm in the test under the condition of using the original GNSS signal. It is possibly explained to be resulting from the influence of the ionospheric error. To further understand, the ionosphere vertical total electron content (TEC) maps, provided by International GNSS Service [15], were used to extract TEC information from the vicinity of the station, i.e. latitude 25° N, longitude 120° E, and altitude 450 m, and compare the two test periods in Fig. 16.

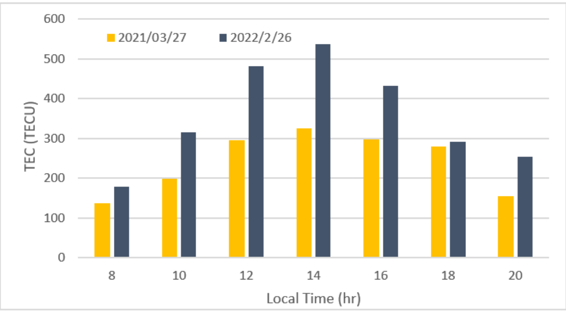


Fig. 16. Comparison of the TECs for the two test periods

From the figure, it can be seen that the TEC values in the second group (February 2022) were all higher in the same period, and the sessions with TEC values above 300 units, e.g. 10-16h local time, also correspond a higher level of positioning errors. However, the exact correlation is suggested to be further investigated.

IV. CONCLUSION AND SUGGESTIONS

In this study, a short baseline PPK positioning using the smartphone received L1 carrier phase observables can provide the following findings:

1. Mi8 smartphone observations could improve the positioning accuracy by 60-80% when using precise ephemeris, instead of using broadcast ephemeris, with an average difference of 10-20 cm. The use of broadcast ephemeris could also lead to a bias of 75 cm in position.

2. The positioning error of the GNSS observables collected by the Mi8 smartphone in the slow-moving state was much larger than that of the fixed-point observations, and the error of moving test could be as high as 90 cm.

3. The external accuracy of smartphone positioning was significantly worse than the internal precision, which might be caused by the smartphone antenna or the signal reception anomaly. Thus, a GNSS signal re-radiator could be used to improve the signal transmission quality.

4. Regarding the number of satellites, estimated position accuracy, GPS L1 cycle slips, and L1 carrier/noise ratio (C/N_0), the quality of the original signal received by the Mi8 smartphone was indeed obviously worse than that of the geodetic receiver. However, the modified GNSS signal obtained using the proposed re-radiating kit could be much better than the original GNSS signal and closer to the signal quality of geodetic receiver.

5. Using the modified GNSS signal in the indoor zero baseline calibration, the error showed that the plane error of the geodetic receiver was 0.7 cm. The zero-baseline error of Mi8 slightly increased to 1.0 cm, and the stability of the performance was relatively poor.

6. In the outdoor environment where the original and modified GNSS signals coexisted, the L1 phase observed by smartphone near to the re-radiating antenna with 3 m could not be received effectively. Meanwhile, the L1 phase could be received for a 10-m baseline, but the positioning error would increase to 59 cm due to the interference of signal coexistence.

7. When the modified GNSS signal was provided in an open space, the re-radiating antenna and smartphone could be blocked from the original signal by sheltering so that the modified signal could show a positioning error of 3-9 cm.

8. During the operating hours from daytime to evening, the positioning error of the modified GNSS signal received by Mi8 with the shelter could be reduced by at least 30% compared with the original signal. The average plane error could be lowered down from 168 cm to 16 cm. However, there were still some hours to see the error greater than 20 cm.

From the test of using GNSS phase observables for short baseline PPK positioning with smartphones, the following suggestions for future development are provided:

1. When the Mi8 smartphone uses the

Geo++ program to receive GNSS observations, only the observation file in the RINEX format is accessible. Thus, the satellite orbit information used for positioning calculation must be provided by other sources.

2. To make the GNSS observations received by the smartphone carry on a centimeter-level positioning, the antenna phase center, the instrument centering and leveling, the signal reception quality, and the influence of ionospheric effect should be continuously studied and overcome.

3. Precise Point Positioning (PPP) will be one of the mainstream technologies. The amount of observations provided by smartphone receivers should be increased with the navigation satellite modernization. Thus, it is worthwhile to explore the topics of using smartphone receivers' L1/L5 dual-frequency carrier phase observables to effectively achieve a decimeter-level positioning in both static and kinematic modes [16].

4. The GNSS signal re-radiating kit can provide the data with better quality, but the positioning performance is still not steadily meet a 20 cm requirement for underground pipeline surveying. However, its equipment and operation has potential to carry out some applications, such as rapid map revision etc. [17].

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