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Evaluation of Positioning Accuracy of Smartphones under Different Canopy Openness

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Abstract: This study focuses on evaluating the positioning accuracy of smartphones in a deciduous forest environment compared to various levels of Global Navigation Satellite System (GNSS) devices. In a mixed coniferous forest with 90% broad-leaved forest (deciduous season), the accuracy of 57 test points was evaluated according to different openness levels under the forest. Taking the coordinates obtained by survey-grade GNSS devices in RTK (Real-time Kinematic) mode as standard, the accuracy of the single-point positioning (SPP) mode and precise-point positioning (PPP) mode obtained by three smartphones (one single frequency and two dual frequency), one survey-grade receiver and one recreational-grade receiver are compared. It can be found that there was a significant positive correlation between canopy openness and carrier-to-noise density(C/N0) ($p < 0.05$). Meanwhile, the C/N0 of survey-grade devices is significantly higher than that of smartphones. The results show that the positioning accuracy of dual-frequency smartphones under forests is better than that of single-frequency smartphones. Furthermore, the positioning accuracy of the smartphone corrected by PPP mode is better than that of the recreational-grade GNSS receiver and can achieve an accuracy of about 2.5 m in the horizontal direction, which can be used for forestry stakeout, reset and determination of forest area boundaries in environments with high openness (R > 0.7). However, in an environment with low openness (R < 0.7) and relatively complex forest area positioning, survey-grade GNSS devices are still required to cooperate with the PPP or real-time differential positioning method to obtain accurate sub-meter-level positioning data.

Keywords: canopy openness; smartphone; GNSS receiver; positioning accuracy; single-point positioning; precise-point positioning

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1. Introduction

Global Navigation Satellite Systems (GNSSs) have rapidly developed in recent decades [1] and are widely used in navigation and mapping, disaster monitoring, and precision agriculture. GNSS positioning research based on multi-system integration has become mainstream [2]. This trend makes GNSS receivers develop polarization. On the one hand, precise work requires survey-grade receivers with positioning accuracy of centimeter level or even millimeter level [3,4]. On the other hand, portable handheld devices can also meet specific needs in navigation and work with low-accuracy requirements [5,6]. In particular, positioning applications for smartphones are popular due to their portability. According to the Ericsson mobile report in June 2018, there are 4.8 billion smartphones using GNSS chipsets worldwide [7]. As a result, smartphones have become the most widely used GNSS location terminal and are used in various mobile services.

Because of the widespread use of smartphone positioning services, people have further started to study the positioning accuracy of smartphones. Lei et al. used smartphones to achieve better accuracy of street positioning in the urban environment [8]; Kenneth et al. evaluated the data sampled by GNSS antennas based on smartphones to achieve centimeter precision positioning [9]. In 2016, Google released the original observation data of Android smart devices, which provides a new idea for researching GNSS navigation and positioning technology based on smart terminals. Scholars can calculate and correct the original positioning data obtained by the intelligent terminal through algorithms or other technologies to improve the accuracy of the equipment [10–12]. In 2018, smartphones were first equipped with dual-frequency GNSS chips. Before that, smart terminals were generally equipped with single-frequency and multi-constellation GNSS chips [13–15]. The development of dual-frequency chips has promoted the rapid application of precise smartphone positioning in the mass market [16,17] and increased the adaptability of smartphones in complex environments. Many scholars' positioning tests on smartphones show that the original measurement quality of dual-frequency GNSS smartphones is generally better than that of single-frequency smartphones. Combining RTK (real-time kinematic) and PPP (precise-point positioning) technology can effectively improve the positioning performance of smartphones [18,19].

The increasingly sophisticated navigation system has played a significant role in forestry, enabling macro control of forest areas and ensuring forestry work's modern and efficient development. Nevertheless, the complicated environment in the forest is undoubtedly a challenge to precise positioning. Due to the complex and diverse forest environment, the signal quality collected by forestry workers using receivers will be affected by terrain or tree canopy [20]. Furthermore, multipath effects will occur when the devices receive space satellite signals due to obstacles (such as tree trunks) between the line and the satellite [21,22]. That will cause significant errors in positioning calculation and even make it impossible to locate [23,24]. Relevant research shows that the complex forest environment has a tremendous adverse impact on receiving the signal by GNSS devices [25–27]. Branches, trunks, and leaves will attenuate, distort, or hinder the forest GNSS signal, so positioning accuracy is significantly lower than those in areas with high openness [28–32].

Previous research on GNSS receivers in forestry found that the positioning accuracy is the lowest in coniferous forests, middle in broad-leaved forests, and the highest in non-forest lands. The average positioning accuracy increases from the valley and hillside to the top of the mountain [33]. Mountainous and steep-terrain environments also pose some obstacles to accurate GNSS positioning. The research is confirmed by Valbuena et al. [23]. Michael's research shows that canopy coverage and open sky have a more significant impact on positioning accuracy than slope degree, slope position, aspect, tree height, canopy depth, or altitude [34]. In addition, Kobayashi et al. [31] and Naesset [35] found that the measurement error of GNSS under the forest increases with the breast-height sectional area of the stand. Compared with the open environment, the forest environment is more complex and the positioning accuracy will be affected by many factors. Therefore, many scholars have tried new positioning methods, such as differential global positioning systems (DGPSs), to improve the accuracy of positioning in the forestry environment [28,36,37].

Currently, the most used positioning instruments for forestry workers in field surveys are smartphones and low-cost receivers (recreational-grade and map-grade receivers) [38]. Smartphones occupy most of the market for low-cost receivers due to their portability and versatility [39]. More and more forestry work is carried out with smartphones as positioning tools. Bianchi et al. used smartphones to collect forest canopy hemispheric images [40]. Vastaranta et al. evaluated the measurement of forest sample plots by smartphone applications [41]. Tomastik et al. used smartphones to measure the wind damage area in the forest [42]. Furthermore, in a study using smartphones to evaluate the positioning accuracy under the forest, Tomastik et al. used three smartphones to obtain the positioning accuracy of 6.74–11.45 m (with leaves) and 4.51–6.72 m (without leaves) under the forest [42], used dual-frequency smartphones to obtain the positioning accuracy of 6.13 m (with leaves) and 4.10 m (without leaves), and evaluated the applicability of the original GNSS data [43]. Guo et al. measured, in the forest environment (with leaves), that the accuracy of smartphones in PPP mode is equivalent to that of recreational-grade GNSS devices and the distance root means squared (DRMS) of medium and high-canopy openness can reach 2.6–4.2 m [44].

However, little research focuses on comparing positioning accuracy between smartphones and GNSS devices at all levels under the forest. As a result, it is unclear whether the real-time measurement results of smartphones and the data results processed by the PPP mode in the forest environment can achieve satisfactory accuracy. Therefore, it is necessary to quantify the positioning accuracy of smartphones in the forest and to investigate the usability of smartphone positioning in the forest environment.

This study aims to quantify the positioning accuracy of smartphones and receivers of various levels in different forest environments by accessing parameters, such as the number of satellites, signal quality, and positioning accuracy. By comparing the differences in positioning accuracy between smartphones and receivers of various levels, we can comprehensively evaluate whether smartphones meet the positioning requirements of forestry work and provide reference opinions for selecting positioning and navigation equipment in different forest canopy openness environments.

2. Materials and Methods

2.1. Test Devices

Three smartphones and two GNSS receivers are used in this experiment. Smartphones: OPPO K9 (hereinafter referred to as K9), Realme GT NEO (NEO) and HUAWEI P50 Pro (P50). GNSS receivers: UniStrong G138BD (G138BD) and HiTarget iRTK2 (iRTK2). The three smartphones used in this paper support all constellation systems, K9 supports receiving single-frequency satellite signals, and the other two mobile phones support receiving dual-frequency satellite signals. The types of satellite systems and signal frequencies supported by each device are shown in Table 1.

Table 1. Satellite systems are supported by every device.

Device Model	Time to Market	Operating System	Acceptable Signal Type of Global Navigation Satellite Systems (GNSS) Device				
			GPS	BDS	GLONASS	Galileo	QZSS
K9	2021	Android 11	L1	B1	L1	E1	L1
NEO	2021	Android 11	L1\L5	B1\B2	L1	E1\E5	L1\L5
P50	2021	Harmony	L1\L5	B1\B2	L1	E1\E5	L1\L5
G138BD	2012	OS2.0	L1	B1	L1	\	\
iRTK2	2014	\	L1\L2\L5	B1\B2\B3	L1\L2\L3	E1\E5a\E5b	L1\L2\L5

The tripod is installed and fixed on the test point to enable the device to stably obtain the positioning data. The tripod is connected with a base and an extension rod. Starfish iRTK2 is placed on the top of the extension rod. Other test devices are fixed on the extension rod in different directions (Figure 1). Each device is about 10 cm away from the extension rod and the placement direction is East: X70; West: NEO, G138BD; South: P50; North: K9. The height between each device and the test point is iRTK2: 2 m; X70; 1.8 m; P50:1.7 m; K9: 1.6 m; NEO:1.5 m; G138BD: 1.3 m. The absolute position of each device is calculated by using the distance and direction from the extension rod and the height to the test point.

2.2. Method

The test site is located in Baoding agricultural ecological park, Hebei Province. The environment is relatively simple and the test interference items are few. Fifty-seven test points are set according to different canopy openness levels (Figure 2). Its accurate coordinates are measured by the iRTK2 system (RTK Positioning Accuracy: plane: $\pm(8 + 1 \times 10^{-6}$ D) mm) in combination with FindCM CORS service (CORS accuracy: horizontal positioning accuracy 2 cm in the ideal environment). To ensure high coordinate accuracy in the test points, first, we used IRTK2 and CORS services to obtain the fixed solution in an open place as the control point of this experiment and then used two iRTK2 devices to measure the accurate coordinates of all test points in real-time difference positioning.

Figure 1. Arrangement of GNSS device.

Before data collection, all smartphones should turn on the flight mode in the setting interface to prevent mobile phone Assisting-GNSS (AGNSS) function from using the base station information to affect the positioning data. The GNSS system supports all multi-mode states and the power-saving mode is turned off during data collection. Before the test, turn on the option of “force to enable comprehensive tracking of GNSS measurement results” in the “developer options” to avoid the impact of the working cycle on the data integrity of this experiment. P50 cannot turn on the option of force to enable comprehensive tracking of GNSS measurement results due to system restrictions. The smartphone measurement program is Geo++ RINEX logger 2.1.6 (Geo++ GmbH, Garbsen, Germany), which records the original GNSS measurement data in RINEX 3.03 format. Most PC GNSS processing software can then process these formats of data. G138BD uses its program to record the original location data and iRTK2 records the current location information through the Hi-Survey Road application. Except that G138BD cannot change the height angle setting, all other devices are set to a height angle of 15°, with a sampling interval of 1 s. In addition, iRTK2 is set to output the observation file in GNS format and the original file in RINEX format simultaneously. This experiment records 10 min at each test point and observed data of about 600 epochs.

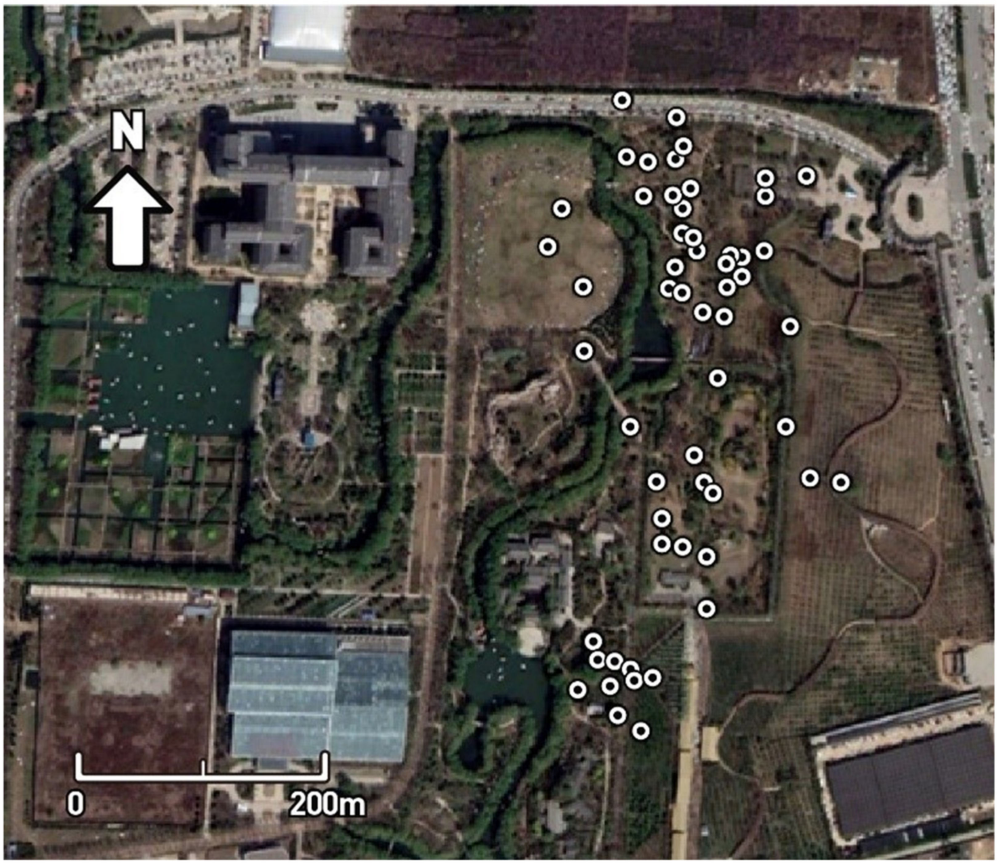

Figure 2. Sketch map of observation points and surrounding trees.

In January 2022, a Cannon EOS 50D digital camera with a sigma ex DG 8 mm fisheye lens was used to take all sky photos 2 m above the test point by hemispherical imaging technology. When taking photos, avoid the interference of surrounding shrubs and other young trees; an automatic balance bracket is used to make the camera lens horizontal and upward. The left side of the device faces north so that the direction can be distinguished during photo analysis. Choose a cloudy day with uniform clouds or set the time close to sunrise (8:00) or sunset (16:00) to avoid direct sunlight and bright spots in the photos. No wind weather shall be selected for shooting and two photos shall be taken at each point to avoid blurring and other problems. Use HemiView 2.1 SR5 software to analyze and process the photos taken. Extract the canopy openness data from the VisSky column in the values worksheet from the processed data. As shown in Figure 3, the three pictures reflect the different forest environments with different degrees of density. They are environments with low, medium, and high-canopy openness from left to right.

Figure 3. The hemispherical photo above represents observation points.

The canopy openness of the 57 test points is shown in Figure 4 and the test points were classified according to different environmental openness. Low openness was defined as forest canopy occupying less than 30% of the sky, medium openness was defined as forest canopy occupying 30% to 50% of the sky, and medium-high openness was defined as forest canopy occupying 50% to 70% of the sky. Finally, high openness was defined as forest canopy occupying more than 70% of the sky. Fifty-seven test points were recorded in January 2022.

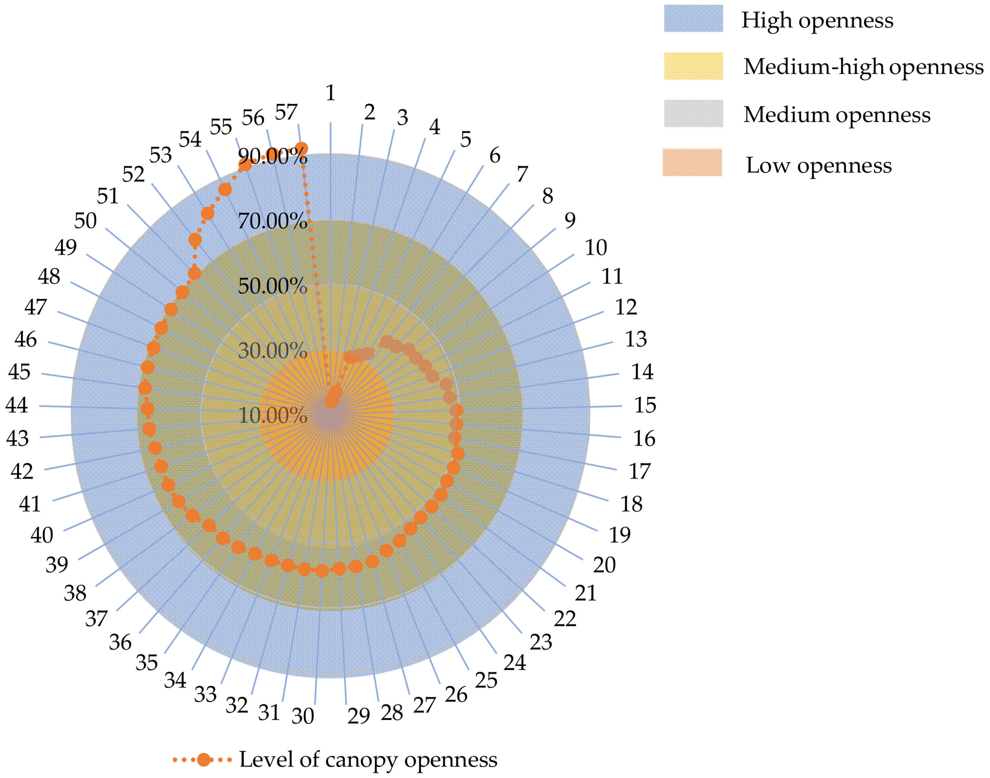

Figure 4. Test points openness and classification.

2.3. Data Processing

G138BD exports waypoint data through GIS Office software and the original data of starfish IRTK2 is directly exported by the device to a CSV format record file on a PC through a USB data cable. RINEX data obtained by smartphones is processed by RTKLIB 2.4.2 software. The following settings need to be selected before using the RTKPOST module in RTKLIB to process original GNSS data: positioning mode: single point/static PPP, frequency: L1 + L5 + E5, filter type: combination, cut off height angle: 15, constellation: GPS + BDS + GLONASS + Galileo + QZSS, integer ambiguity solution: continuous signal processing. After processing the original observation data with RTKPOST, use RTKPLOT module to draw the image, which can visually compare the distance and direction of the coordinates of the observation value and the coordinates of the test point and provide basic error statistical information (mean value and standard deviation). HGO v2.0.4 software is used to convert geographical coordinates and projection coordinates in the experimental data.

The root mean square horizontal error (RMS_{xy}), one of the most common accuracy measurement methods in geodesy, is used as the primary index to compare the positioning accuracy of devices.

The first step is to calculate the root mean square X and Y coordinate errors:

$$RMS_x = \sqrt{\frac{\sum_{i=1}^{n} \Delta X_i^2}{n}} \quad RMS_y = \sqrt{\frac{\sum_{i=1}^{n} \Delta y_i^2}{n}}$$

where Δx_i and Δy_i are the average coordinate error, which is the difference between the measured value of GNSS and the actual value, and n is the number of epochs. Then calculate the root mean square horizontal error RMS_{xy} as follows:

$$RMS_{xy} = \sqrt{\left(RMS_x^2 + RMS_y^2\right)}$$

Compare the error of the tested devices with the minimum value, maximum value, average value, and standard deviation (SD). The statistical software SPSS24 was used for the one-way analysis of variance (ANOVA) of least significant difference (LSD) post test to evaluate the differences between devices and different canopy openness. The mean value, standard deviation, maximum value, and minimum value of the position error obtained at different test points are used to evaluate the impact of different canopy openness on positioning accuracy. The design of the experimental method and the steps of data processing are well illustrated in Figure 5.

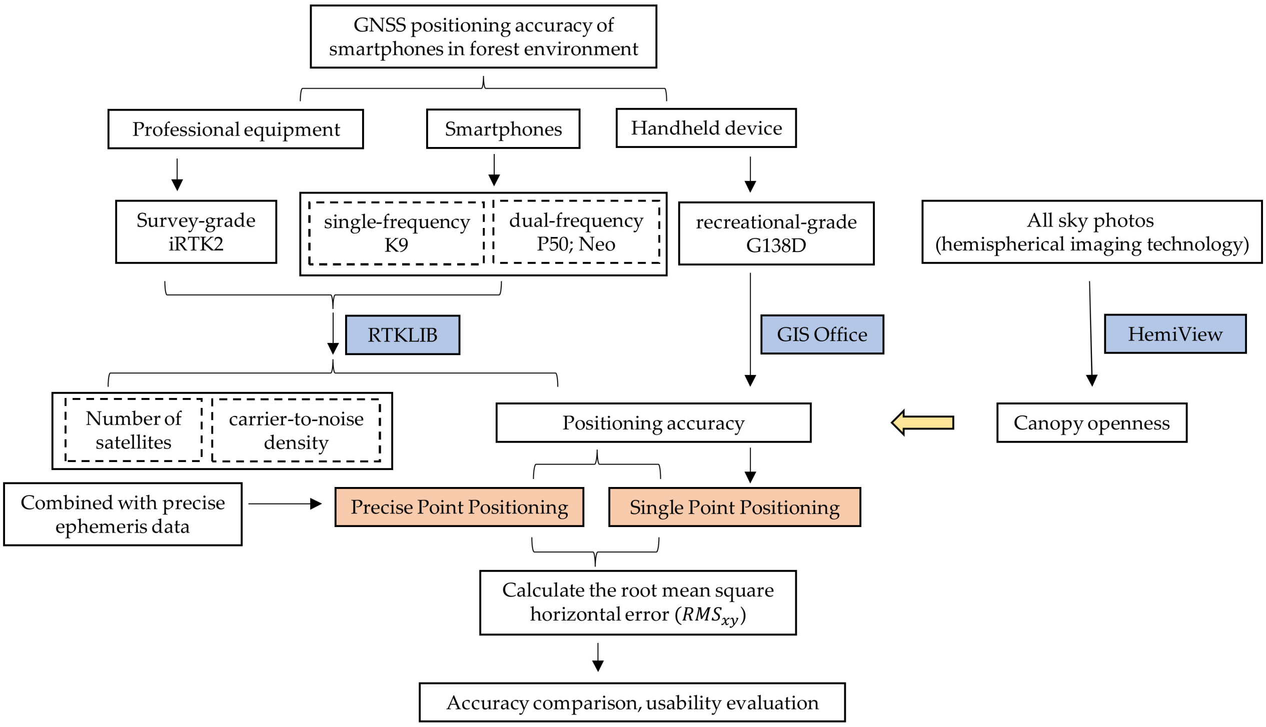

Figure 5. Methodology and data processing flow chart.

3. Results

3.1. Influence of Canopy Openness on the Number of Observation Satellites and Signal Quality

3.1.1. Influence of Canopy Openness and Equipment on the Number of Available Satellites

The number of available satellites is mainly affected by its spatial geometric distribution and the ability of the receiver to search for satellites. According to the statistics of the number of satellites available for each device (Figure 6), multi-system devices can capture enough satellites during positioning measurement when GNSS devices are carried out in an open environment. With the increase in the canopy openness, the number of satellites available for each device increases exponentially. For example, the average number of available satellites of the two dual-frequency smartphones is higher than that of the single-frequency smartphones. The number of available satellites for the dual-frequency smartphone P50 is higher than that of survey-grade devices (the average number of satellites searched is 34). Even in the most sheltered environment (p < 0.3), each device can obtain the support of at least 15 satellites. This, by some distance, meets the requirements for the number of satellites measured by GNSS.

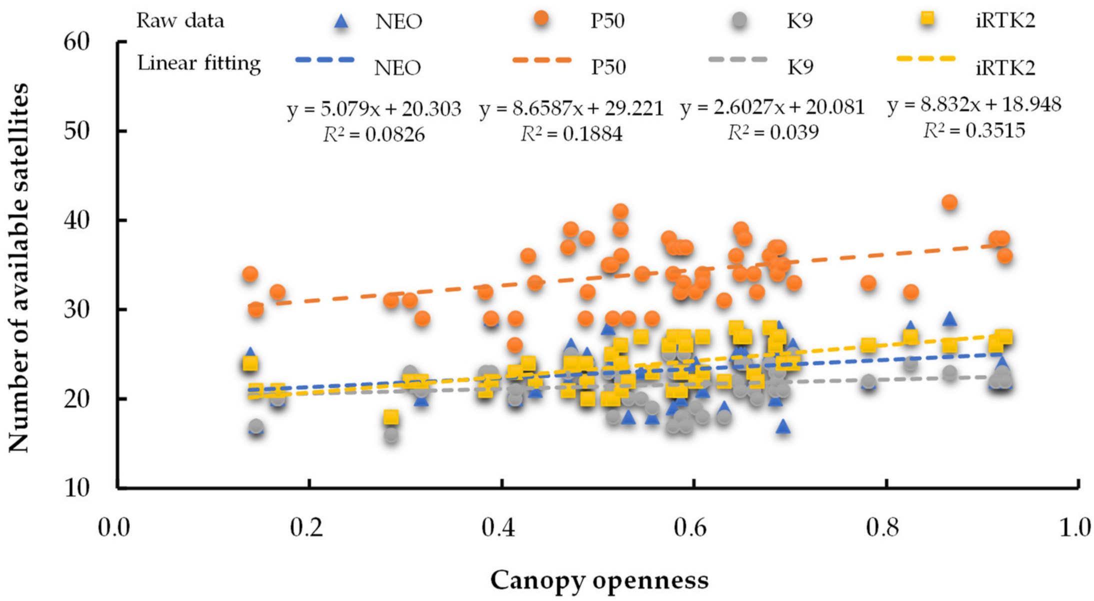

Figure 6. The number of available satellites with different canopy openness.

In SPSS24, one-way ANOVA and post-LSD test were performed on the number of available satellites of each piece of equipment under different opening conditions (0.14~0.92) to test the difference in devices under different opening conditions (Figure 7). It is found that the stability of satellite search of single-frequency smartphones is poor. When dual-frequency smartphones are in a range of openness above 0.3, the number of available satellites tends to stabilize. The average number of available satellites of NEO is 23 and the average number of available satellites of P50 is 34. Due to the high requirements for satellite signal quality, survey-grade GNSS devices can track satellites more stably when the openness is more than 0.5. The average number of available satellites is 24. In addition, the poor satellite search stability of single-frequency mobile phones makes no significant correlation between the number of available satellites and the openness of the forest (Table 2). However, the number of available satellites of dual-frequency smartphones and measurement-level devices is moderately correlated with the openness of the forest ($p < 0.05$).

3.1.2. Influence of Canopy Openness and Equipment on Carrier-to-Noise Density

The carrier-to-noise density (C/N0) has a significant impact on the positioning accuracy of the devices. A low C/N0 indicates that the satellite signal obtained by the receiver contains a lot of noise, which will cause a significant positioning drift probability. GPS satellites can transmit L1 and L5 frequency signals and Galileo satellites can transmit E1 and E5A frequency signals. The L1/E1 and L5/E5a frequencies of GPS and Galileo are no longer distinguished in subsequent data, collectively referred to as L1 and L5 frequencies. Comparing the average C/N0 of the L1 frequency of different devices (Figure 8), it is found that under the same measurement environment, the average C/N0 of the L1 frequency of smartphones is significantly lower than that of survey-grade GNSS receivers. The C/N0 of smartphones is generally lower than 35 dB under medium- and low-openness conditions, indicating that the data packets contain much noise. Although the smartphone K9 only supports a single-frequency, the C/N0 of L1 frequency is better than NEO with more advanced hardware. The C/N0 is not only related to the configuration of devices but also closely related to antenna design, transceiver power, and other factors. The L1 frequency C/N0o of iRTK2 is generally above 40 dB and the highest can even reach 45 dB, which is significantly higher than smartphones. L5 frequency is similar to L1 frequency and there is a large gap between the C/N0 of smartphones and survey-grade GNSS devices.

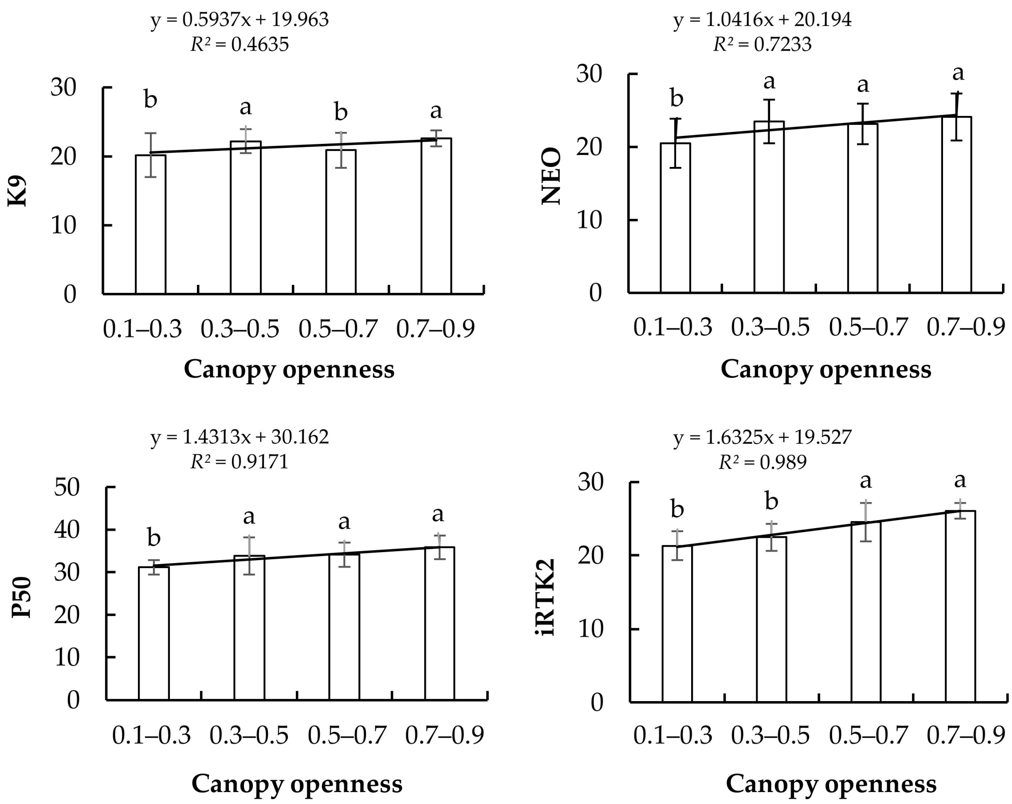

Figure 7. The number of available satellites with different canopy openness. Note: different letters in the figure indicate significant differences.

Table 2. Correlation of canopy openness to the number of available satellites.

	K9	NEO	P50	IRTK2
Correlation coefficient	0.155	0.304	0.339	0.612
Significance	0.250	0.048	0.010	0.001

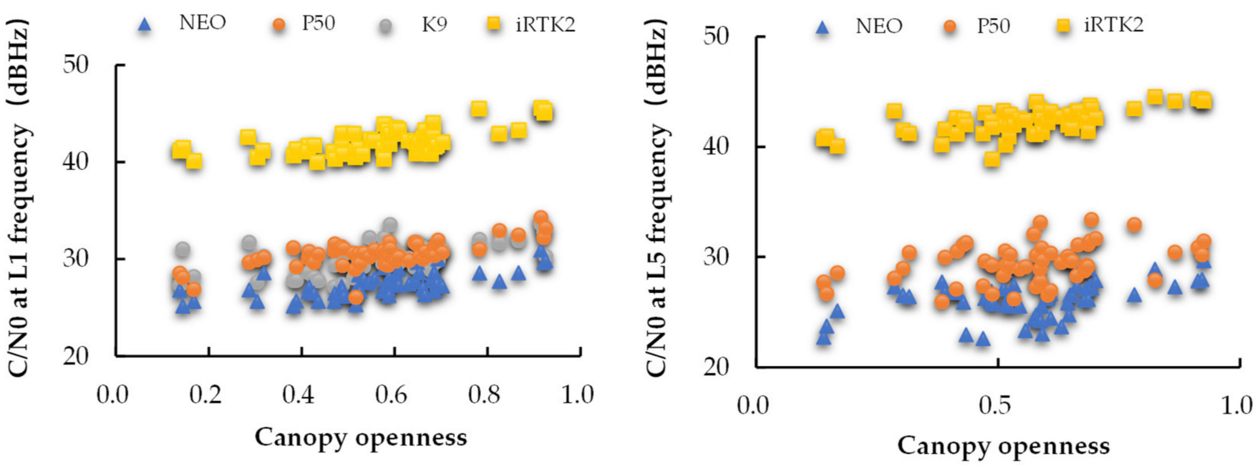

Figure 8. Carrier-to-noise density(C/N0) at L1 and L5 frequencies.

As shown in Table 3, the single-factor ANOVA variance test in SPSS24 and post LSD are used to compare the difference in the C/N0 of the test equipment under different openness conditions. The results show that the L1 frequency C/N0 of the single-frequency smartphone K9 is relatively stable in a high-opening environment (0.5–0.9), up to about

30 dBHz. On the other hand, the C/N0 of dual-frequency smartphones at L1 and L5 frequencies is smaller when the openness is greater than 0.7 and the C/N0 is between 27.74 and 31.89 dB.

Table 3. C/N0 of each device at different openness.

Device Mode	Signal Frequency	Canopy Openness			
		0.1–0.3	0.3–0.5	0.5–0.7	0.7–0.9
K9	L1	29.35 ± 1.88 b	28.74 ± 1.05 b	30.46 ± 1.21 a	30.99 ± 1.56 a
NEO	L1	26.43 ± 1.25 c	26.42 ± 0.80 c	27.70 ± 0.86 b	28.64 ± 1.26 a
	L5	25.30 ± 1.77 b	26.15 ± 1.50 b	25.91 ± 1.72 b	27.74 ± 1.03 a
P50	L1	28.87 ± 1.27 c	30.08 ± 1.29 b	30.56 ± 0.69 b	31.89 ± 1.16 a
	L5	28.41 ± 1.25 b	29.11 ± 1.56 b	29.30 ± 1.71 b	30.82 ± 1.57 a
iRTK2	L1	41.16 ± 0.85 c	41.28 ± 0.79 c	42.25 ± 0.99 b	43.48 ± 1.56 a
	L5	41.29 ± 1.09 c	41.68 ± 1.17 c	42.57 ± 0.78 b	43.42 ± 1.02 a

Note: Different letters in the same row in the table indicate significant differences, where "±" represents the standard deviation.

Smartphones need to be in a relatively open environment to obtain high-quality satellite signals. Dual-frequency smartphone NEO may have poor signal acquisition ability due to its chip or antenna design and the C/N0 fails to reach 30 dB at L1 and L5 frequencies, especially at L5. This will also lead to low accuracy in pseudo-range single-point positioning. The C/N0 of survey-grade GNSS devices at L1/L5 frequencies and the differences in various environments are very similar. In an environment with high-canopy openness (0.5–0.9), the C/N0 is 42 dB–43 dB. Even in an environment with low-canopy openness (0.1–0.3), the C/N0 is generally higher than 41.16 dBHz. This is because IRTK2 has high hardware specifications and a strong signal-receiving ability to ensure positioning quality.

Table 4 shows a very significant positive correlation between the C/N0 of each device and the canopy openness using Spearman correlation analysis with SPSS24. The correlation coefficient of the C/N0 of the L1 frequency of smartphones is significantly higher than that of the L5 frequency, while the correlation of the two frequencies is almost the same for the survey-grade device. In addition, according to the comparison of the mean, minimum, and maximum C/N0 of L1 and L5 of three dual-frequency devices (NEO, P50, and iRTK2) (Figure 9), it can be found that the C/N0 of smartphone L5 frequency is significantly lower than its L1 frequency in various open environments. This shows that the smartphone GNSS chip has a large gap with L1 frequency in using the L5 frequency signal.

Table 4. Correlation between C/N0 and canopy openness.

Device Mode	K9	NEO		P50		iRTK2	
	L1	L1	L5	L1	L5	L1	L5
Correlation coefficient	0.492	0.641	0.363	0.625	0.392	0.601	0.591
Significance	0.001	0.001	0.006	0.001	0.003	0.001	0.001

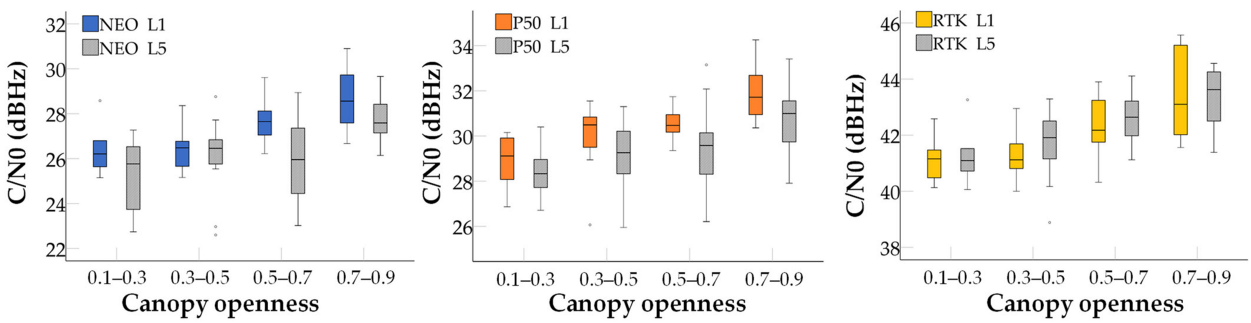

Figure 9. Comparison of C/N0 of NEO, P50, and iRTK2 in L1 and L5 frequencies.

3.2. Relationship between Canopy Openness and Positioning Accuracy in Single-Point Positioning (SPP) Mode

Except for the recreational-grade device G138BD, the positioning accuracy of each device improves with the increase in openness, as shown in Table 5 and Figure 10. The horizontal accuracy difference in G138BD in various canopy openness is insignificant ($p > 0.05$) and the rest of the device is generally stable when the canopy openness is more than 0.7. In Table 5, the errors in the east, west, and elevation directions are expressed as the root mean square error (RMS) and the errors in the horizontal direction are expressed as the distance root mean square error (DRMS). In general, when the canopy openness of the smartphone is greater than 0.7 in the east, north, and horizontal directions, the positioning accuracy is between 4.62 and 7.67 m. The positioning accuracy of dual-frequency mobile phones is better than that of single-frequency mobile phones in both horizontal and vertical directions. The precision of pseudo-range single-point positioning of survey-grade receivers is much higher than that of smartphones, which is about 3–8-times that of smartphones. When the canopy openness is greater than 0.7, it can reach sub-meter precision in east, north, and horizontal directions. The accuracy of recreational-grade devices is about 1.2–3-times that of smartphones and the average positioning accuracy in east, north, and horizontal directions is between 2.18 and 4.75 m. The influence of the difference in the original data quality of different devices on the positioning is more obvious in the elevation direction. The positioning accuracy of each device in the elevation direction is generally low and the error is about twice the positioning accuracy of the corresponding opening in the east or north direction.

Table 5. Positioning accuracy of each device in single-point positioning (SPP) mode.

Error Direction	Device Mode	Canopy Openness			
		0.1–0.3	**0.3–0.5**	**0.5–0.7**	**0.7–0.9**
East direction (m)	K9	8.36 ± 4.38 b	8.00 ± 3.98 b	6.70 ± 2.48 b	4.95 ± 1.80 a
	NEO	7.89 ± 3.64 b	7.02 ± 2.36 b	5.41 ± 1.49 a	4.70 ± 2.00 a
	P50	5.71 ± 1.12 a	7.83 ± 3.91 b	5.47 ± 2.17 a	4.62 ± 1.86 a
	G138BD	3.67 ± 1.82 b	2.88 ± 1.20 ab	2.38 ± 0.82 a	2.18 ± 1.51 a
	iRTK2	1.35 ± 0.84 b	1.60 ± 1.06 b	1.06 ± 0.51 ab	0.63 ± 0.39 a
North direction (m)	K9	7.99 ± 1.91 b	9.30 ± 4.05 b	7.61 ± 1.78 b	5.67 ± 2.13 a
	NEO	7.75 ± 2.56 b	8.42 ± 2.58 b	7.24 ± 2.65 b	5.03 ± 2.23 a
	P50	6.90 ± 2.18 b	7.72 ± 2.24 b	6.92 ± 2.61 b	5.20 ± 2.15 a
	G138BD	2.85 ± 0.81 a	3.53 ± 0.90 a	2.85 ± 1.47 a	3.36 ± 1.55 a
	iRTK2	1.49 ± 0.49 b	1.61 ± 0.73 b	1.52 ± 0.51 b	0.86 ± 0.54 a
Elevation direction (m)	K9	16.72 ± 6.10 ab	18.19 ± 7.91 b	14.84 ± 4.65 a	13.03 ± 5.80 a
	NEO	14.42 ± 5.25 a	16.72 ± 5.99 b	16.45 ± 4.76 b	12.99 ± 5.86 a
	P50	11.67 ± 3.33 a	16.95 ± 5.44 b	14.46 ± 4.68 b	11.18 ± 3.90 a
	G138BD	13.10 ± 1.68 bc	12.99 ± 2.36 c	11.26 ± 2.54 b	9.48 ± 2.31 a
	iRTK2	3.65 ± 0.83 a	3.76 ± 1.62 a	3.45 ± 1.12 a	2.79 ± 1.56 a
Horizontal direction (m)	K9	11.91 ± 3.61 b	12.35 ± 5.46 b	10.28 ± 2.50 b	7.67 ± 2.29 a
	NEO	11.10 ± 4.31 b	11.03 ± 2.17 b	9.11 ± 2.81 b	6.96 ± 2.81 a
	P50	9.03 ± 2.07 ab	10.51 ± 2.80 b	9.54 ± 2.73 b	7.04 ± 2.09 a
	G138BD	4.75 ± 1.66 a	4.65 ± 1.16 a	3.89 ± 1.18 a	4.29 ± 1.42 a
	iRTK2	2.08 ± 0.78 b	1.99 ± 0.54 b	1.85 ± 0.67 b	0.99 ± 0.48 a

Note: Different letters in the same row in the table indicate significant differences, where "±" represents standard deviation.

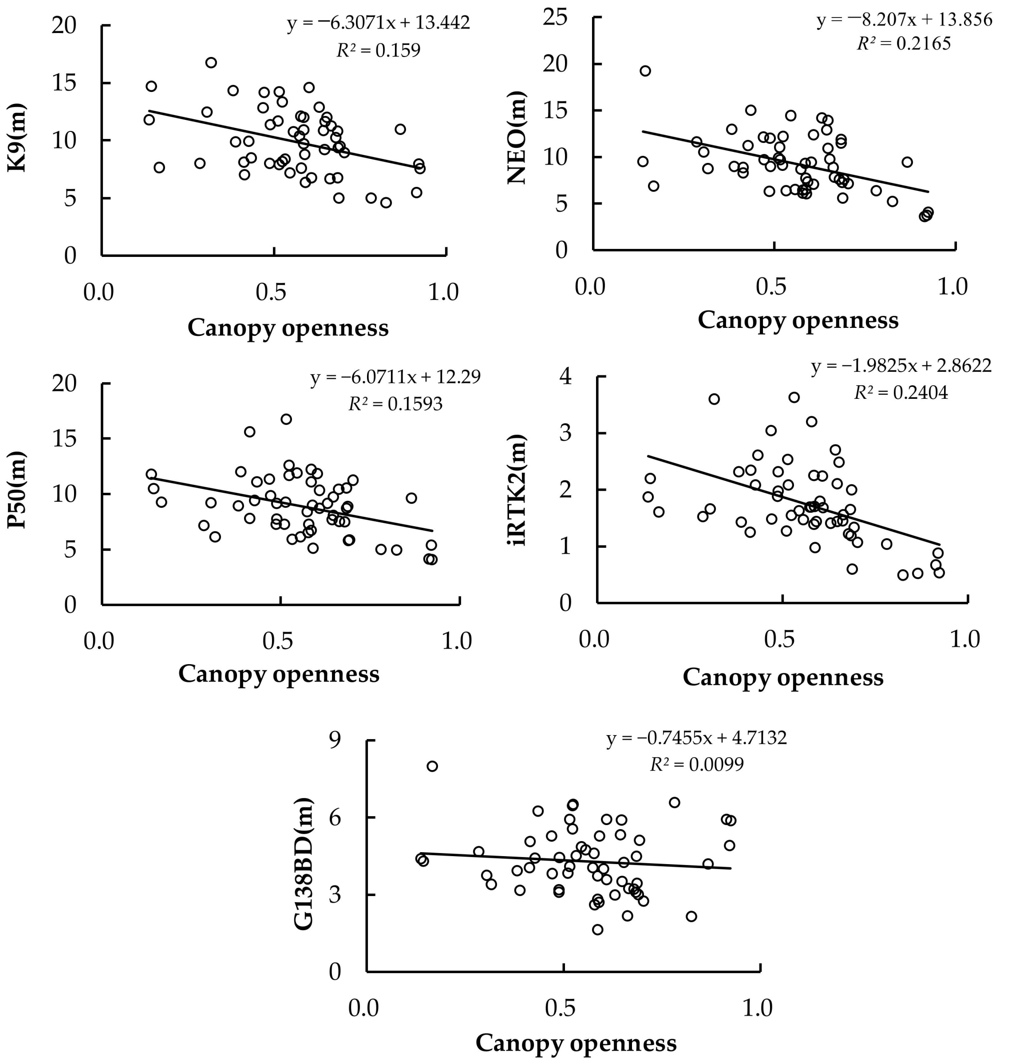

Figure 10. Horizontal distance root mean square error (DRMS) of SPP model under different openness.

There is a linear relationship between the openness and the plane positioning accuracy in the pseudo-range single-point mode (Figure 10). Both the survey-grade receiver iRTK2 and the recreational-grade receiver G138BD can reach the meter accuracy level. However, the accuracy of G138BD in the high-openness environment has not changed significantly compared with medium and low openness. This phenomenon is quite different from iRTK2. The reason may be that the data presented by G138BD are not obtained in the original pseudo-range single-point positioning mode, which internal algorithms have processed, and the overall accuracy decreases with the environment. This phenomenon is similar to the effect of each device treated by the PPP method.

The canopy openness under the forest has a great influence on the positioning accuracy of the device. Without any processing, only the survey-grade device can obtain relatively stable original positioning data, which has high positioning availability in forestry work. In SPP mode, the horizontal accuracy of smartphones is low and there are significant limitations in forestry work. Although the positioning accuracy of dual-frequency smartphones is improved compared with that of single-frequency smartphones, there is still a big gap compared with the survey-grade device, which can only meet the needs of recording the approximate location of sample plots or rough navigation in forest areas and playing an auxiliary role in forest land restoration. Suppose such work needs low positioning accuracy. Try to choose dual-frequency full-mode smartphones. Smartphones are not competent for measuring forest boundaries, forest resource surveys, and other work requiring high accuracy.

3.3. Correction of Raw Location Data of Smartphone by PPP Mode

After correcting by PPP mode, the survey-grade receiver iRTK2 still has the highest accuracy among all devices (Table 6). In the east and north directions, when the canopy openness is between 0.1 and 0.7, the smartphone can reach a positioning accuracy of about 3 m. When the canopy openness is greater than 0.7, it can reach positioning accuracy of about 1.5 m. Overall, it is better than the recreational-grade receiver G138BD. The measurement-level devices can maintain sub-meter accuracy under each canopy openness. In the horizontal direction, when the canopy openness is between 0.1 and 0.7, the smartphone can reach the positioning accuracy within 5 m and the measurement-level devices can reach the positioning accuracy within 1.5 m; when the canopy openness is greater than 0.7, the smartphone can reach positioning accuracy of about 2.5 m and the measurement-level devices can reach the sub-meter accuracy.

Table 6. Positioning accuracy of each device in precise-point positioning (PPP) mode.

Error Direction	Device Mode	Canopy Openness			
		0.1–0.3	0.3–0.5	0.5–0.7	0.7–0.9
East direction (m)	K9	1.94 ± 1.47 a	2.45 ± 2.10 a	2.16 ± 1.85 a	1.53 ± 1.66 a
	NEO	3.48 ± 2.53 b	2.60 ± 1.73 ab	3.04 ± 2.17 b	1.40 ± 1.60 a
	P50	1.85 ± 1.74 ab	1.89 ± 1.44 b	1.07 ± 0.87 a	1.29 ± 0.78 ab
	iRTK2	0.80 ± 1.02 a	0.70 ± 0.54 a	0.46 ± 0.37 a	0.40 ± 0.38 a
North direction (m)	K9	3.45 ± 1.85 ab	3.77 ± 3.03 b	3.36 ± 2.81 ab	1.69 ± 1.64 a
	NEO	2.07 ± 1.30 a	2.92 ± 2.18 a	3.16 ± 2.38 a	1.73 ± 1.41 a
	P50	2.86 ± 2.16 b	1.79 ± 0.97 ab	1.48 ± 1.37 a	2.17 ± 1.61 ab
	iRTK2	0.87 ± 0.46 a	0.84 ± 0.85 a	0.82 ± 0.45 a	0.59 ± 0.53 a
Elevation direction (m)	K9	4.43 ± 3.52 a	4.10 ± 4.24 a	4.84 ± 4.55 a	2.51 ± 3.54 a
	NEO	3.02 ± 1.93 a	3.77 ± 2.53 a	3.75 ± 2.55 a	3.94 ± 2.22 a
	P50	1.59 ± 0.89 b	4.62 ± 2.55 a	4.67 ± 3.27 a	4.16 ± 3.42 ab
	iRTK2	1.23 ± 1.07 a	1.74 ± 1.38 a	1.90 ± 1.52 a	2.27 ± 1.78 a
Horizontal direction (m)	K9	4.10 ± 2.04 ab	4.66 ± 3.45 b	4.50 ± 2.58 b	2.69 ± 1.80 a
	NEO	4.24 ± 2.48 b	4.23 ± 2.22 b	4.61 ± 2.84 b	2.43 ± 1.88 a
	P50	3.96 ± 1.67 b	2.82 ± 1.33 ab	2.01 ± 1.37 a	2.69 ± 1.50 ab
	iRTK2	1.35 ± 0.85 b	1.25 ± 0.80 b	1.01 ± 0.44 ab	0.75 ± 0.60 a

Note: Different letters in the same row in the table indicate significant differences, where "±" represents standard deviation.

In addition, compared with SPP mode, the variation trend in each device with the openness in PPP mode is weakened. The horizontal positioning accuracy of devices in each opening range is mostly not significantly different ($p > 0.05$). In the horizontal direction, under the PPP mode, the average positioning accuracy of each openness range of the smartphone can reach within 5 m. Under the high-opening environment (0.7–0.9), the average positioning accuracy can reach within 3 m.

The relationship between canopy openness and plane positioning accuracy by PPP mode is shown in Figure 11. Compared with pseudo-range single-point mode, its R2 of the fitting equation of the positioning accuracy varies with openness decreases. The main reason is that the greater the error and the better the data quality, the more obvious the accuracy improvement in the PPP mode. As a result, the positioning accuracy tends to weaken with the canopy openness, so the accuracy of measuring points in the figure is more dispersed than that of the SPP mode.

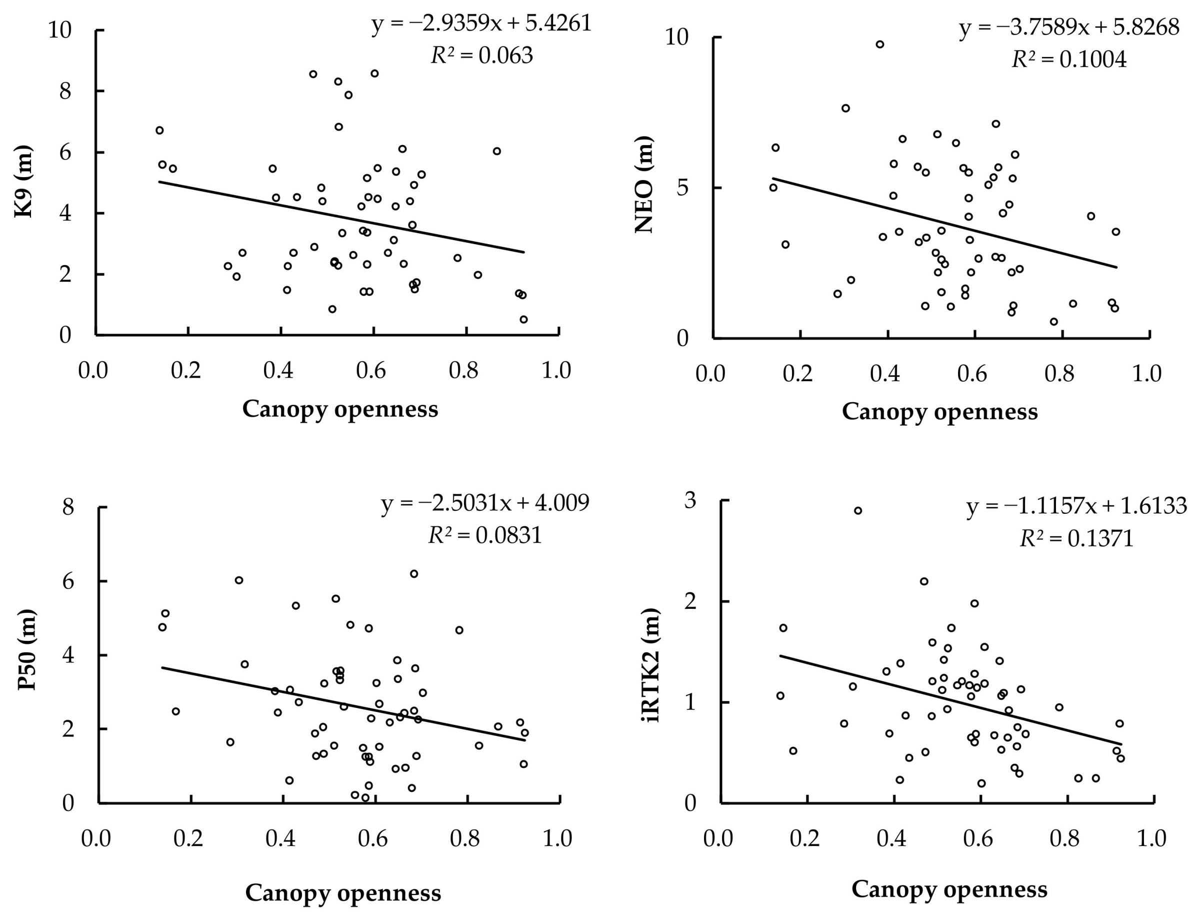

Figure 11. Horizontal DRMS of the PPP model under different openness.

After correcting the raw data from the three smartphones in PPP mode, compared with the pseudo-range single-point positioning mode, the plane positioning accuracy is improved by 2–4-times (Figure 12). The difference between single- and dual-frequency smartphones is not obvious under low openness (openness 0.1–0.3) and the accuracy is about 4 m; when the openness is medium and medium-high (0.3–0.7), the performance is that the single-frequency mobile phone K9 is similar to the dual-frequency mobile phone NEO. The accuracy is still about 4 m. In contrast, the dual-frequency mobile phone P50 can reach 2–3 m. This is because the dual-frequency signal and the raw data with high robustness are more conducive to the correction of PPP mode. However, the C/N0 of dual-frequency mobile phone NEO is low and the quality of the raw data obtained is poor, so the improvement effect of PPP mode is limited. Under high openness (0.7–0.9), the three smartphones can achieve horizontal accuracy of about 3 m. Compared with the data processed by the internal algorithm of the recreational-grade GNSS receiver, the horizontal accuracy of the smartphone after PPP algorithm correcting is similar in the low-openness environment (0.1–0.3) and the smartphone is slightly better, while in the medium and medium-high openness condition (0.3–0.7), the horizontal accuracy of dual-frequency smartphone P50 is significantly better than that of recreational-grade devices. In the high-openness environment (0.7–0.9), the horizontal accuracy of each smartphone is significantly better than that of recreational-grade devices.

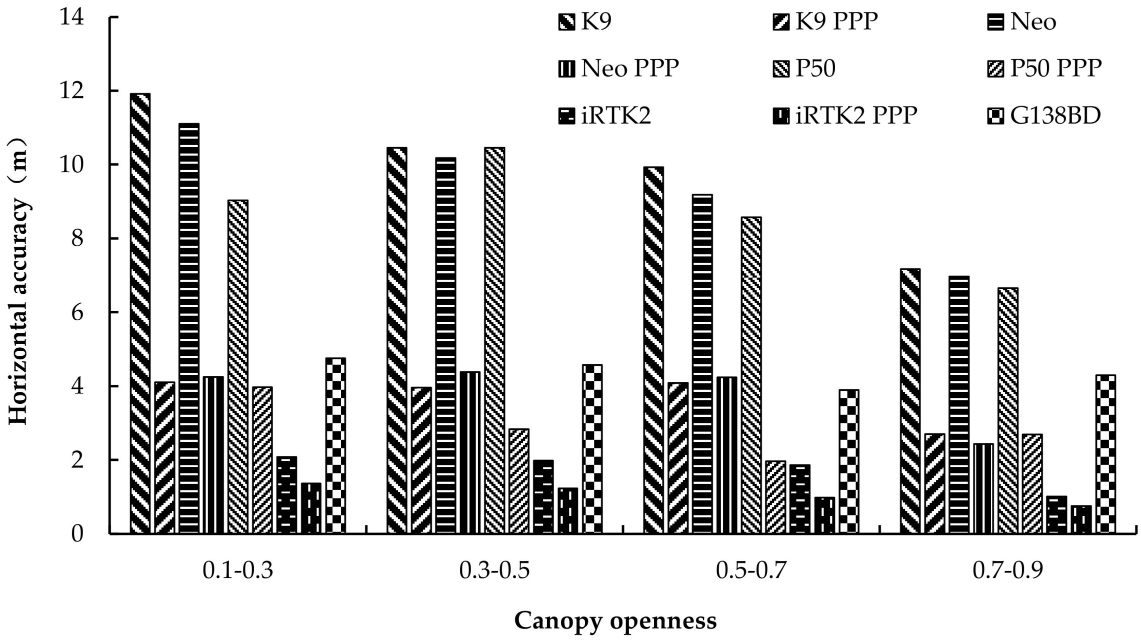

Figure 12. Horizontal accuracy comparison between SPP model and PPP model. Note: In the legend, if the device model is not marked, it refers to the accuracy of SPP, while marked PPP refers to the positioning accuracy processed by PPP technology.

In general, the location availability of the post-processing mode of smartphones in a forest environment is at the same level as that of recreational-grade GNSS receivers. In the forest gap and forest edge environment, it can better complete forestry investigation, afforestation construction setting out, and determine the boundary and area of forest areas. However, when positioning in a forest with extremely low-canopy openness or a complex environment, survey GNSS devices and real-time kinematic (RTK) dynamic differential positioning technology are still needed to obtain more reliable positioning data.

Select the dual-frequency smartphone P50 with high positioning accuracy among smartphones and the survey-grade device iRTK2 and compare their original positioning data at a certain test point (Figure 13A). The original data measured by iRTK2, a survey-grade device, is more concentrated and closer to the test point's accurate coordinates (0,0). The measured accuracy is 2.03 m in the north direction, 0.83 m in the east direction, and the horizontal accuracy (DRMS) is 2.20 M. The original data measured by the dual-frequency smartphone P50 is more accurate, with large dispersion of coordinates and large positioning error. The measured accuracy in the north direction is 8.40 m, the accuracy in the east direction is 12.09 m, and the horizontal accuracy is 14.72 m. There is still a large gap between smartphones and survey-grade devices.

According to Figure 13B, the P50 and iRTK2 devices greatly improved the data dispersion and positioning accuracy after PPP-mode processing. iRTK2 device's data are relatively concentrated and closer to the exact coordinates of the test point (0,0) and the measurement accuracy is 1.70 m in the north direction, 0.34 m in the east direction, and 1.73 m in the horizontal accuracy (DRMS). While the smartphone P50 is relatively scattered, the positioning accuracy is significantly improved compared with the original data. The accuracy was 0.93 m in the north direction, 5.05 m in the east direction, and 5.13 m in the horizontal. The improvement in positioning accuracy of the smartphone corrected by PPP mode is greater than that of the iRTK2 device.

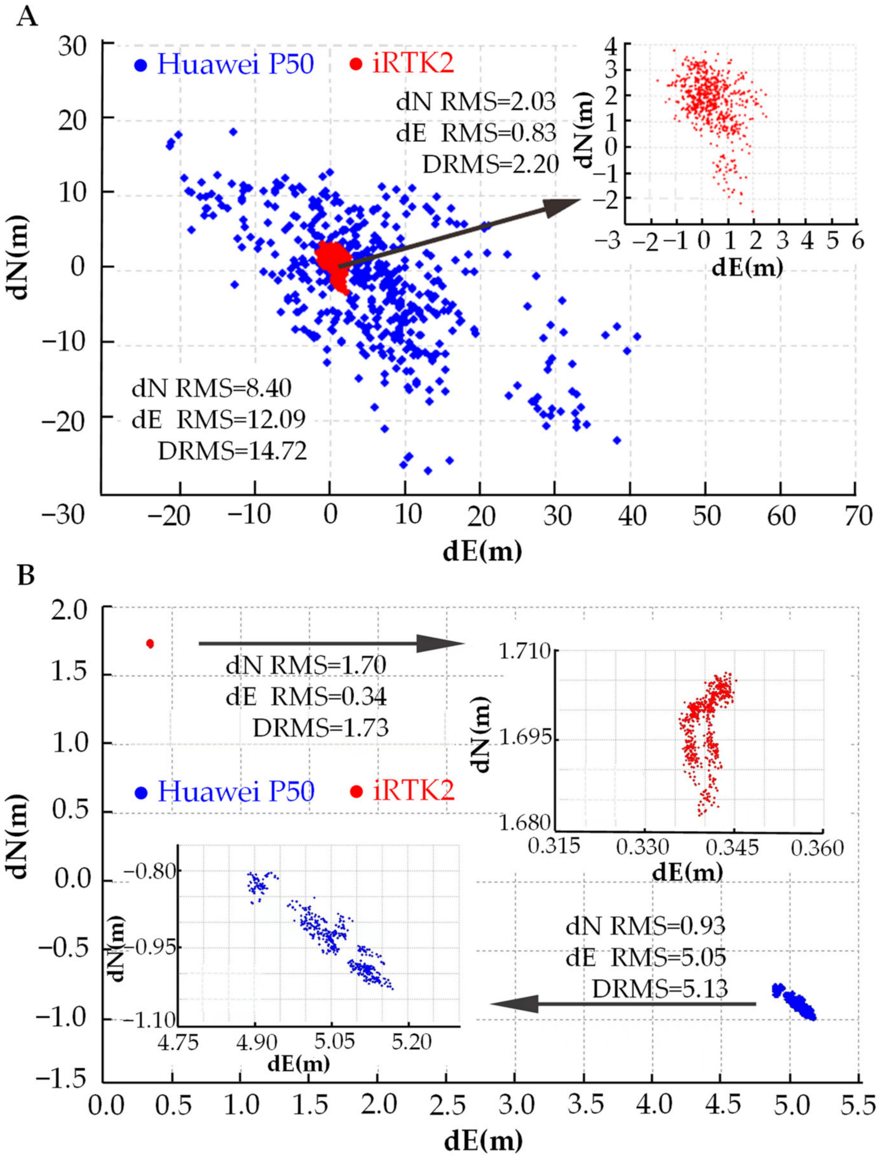

Figure 13. Comparison of positioning accuracy between dual-frequency smartphone P50 and survey-grade receiver iRTK2 in SPP model (**A**); comparison of positioning accuracy between dual-frequency smartphone P50 and survey-grade receiver iRTK2 in PPP model (**B**).

4. Discussion

4.1. Number of Observation Satellites and Signal Quality of GNSS Devices in a Forest Environment

The quality of satellite signals received by GNSS devices in a forest environment is affected by many factors, the most important of which are canopy openness and terrain [45,46]. Due to the influence of canopy openness [46,47], canopy coverage [47], and tree height [48], the more serious the occlusion, the less the number of visible satellites [49]. It can be seen that the number of satellites in previous studies shows a law of increasing with the expansion of the observation site [50]. However, this is not the case in the forest environment. This may be because the canopy is not completely closed and the satellite signal can penetrate the gap between the canopy to reach the receiver during the movement so that some satellite signals will be recorded by the receiver intermittently during the observation process, resulting in no significant change in the number of visible satellites under different canopy-openness conditions ($p > 0.05$). When the number of visible satellites is small, the receiver can also track more satellites. When the canopy openness is large, the number of satellites tracked is not necessarily large [51]. However, from the perspective of actual observation results, some satellites account for less than 20% of the total observation time when the canopy openness is low. These satellite signals have a very limited role in device positioning.

This study found a significant positive correlation between canopy openness and C/N0 of each device in a forest environment ($p < 0.01$). With the increase in canopy openness, the satellite C/N0 increased linearly and evenly. When the canopy openness is more than 0.7, the increase in canopy openness significantly promoted the C/N0. This phenomenon is significantly different from the measurement results in the leafy season [44]. In the case of the leaves season, there is a threshold value for the promotion effect of canopy openness on the C/N0 and the C/N0 increases exponentially with the increase in canopy openness. When the openness is below 0.55, increasing the openness can make the C/N0 increase rapidly. In addition, ANOVA of C/N0 and pseudo-range single-point positioning accuracy shows that even in the most unfavorable environment (the canopy openness is between 0.1 and 0.3), the C/N0 is generally higher than 41.16 dBHz. In contrast, the C/N0 of smartphones is generally lower than 31.89 dBHz, even with the high-canopy openness (0.7–0.9).

4.2. Original Positioning Accuracy of GNSS Devices under the Forest

The existing accuracy research of GNSS receivers mainly focuses on horizontal accuracy. For example, in forestry, how different forest conditions, especially canopy cover, affect horizontal accuracy is the focus of research [52]. The canopy openness has a decisive impact on horizontal and vertical position accuracy. The impact on the positioning accuracy is even more than an order of magnitude [53]. This study found a linear relationship between the canopy openness and the positioning accuracy of the device in the deciduous season. Nevertheless, in the common openness range (0.1–0.7), the horizontal accuracy of the device did not change significantly with the increase in the canopy openness. Previous leafy season tests showed an exponential function relationship between canopy openness and device positioning accuracy. When the canopy openness was less than 0.4, a small reduction in the openness would lead to a significant increase in device position error [44]. The error generally follows the rule that the vertical position error is about twice the horizontal position error [48].

Some scholars found that the newer mobile phone models are better than the old ones in terms of the number of satellites and signal quality. However, the positioning accuracy is not necessarily better [54]. The application of dual-frequency technology in smartphones has made great progress in obtaining raw data quality [14]. Compared with single-frequency smartphones, multi-constellation and frequency receivers provide a more stable and accurate positioning solution. In this test, P50 with a dual-frequency signal has the highest positioning accuracy. However, in general, there are many outliers in the original position observation data of smartphones. In practice, it is often best to use the coordinates of the known position to compare with the measured values for accuracy testing [55]. In addition, it is necessary to study the applicability of smartphone raw GNSS data in a forest environment because the observed data are very vulnerable to multipath and other complex adverse factors.

Many studies proved that smartphone positioning can achieve sub-meter or even centimeter accuracy under open conditions [6,56–58]. Although the new generation of smartphones provides good accuracy in open environments, achieving the same results in forest conditions is difficult. In the forest, the error of smartphone positioning is high. In this test, the untreated real-time measurement accuracy of the common open openness environment (0.1–0.7) is best to reach only about 5 m. The average accuracy difference between the pseudo-range single-point positioning of single- and dual-frequency smartphones is small, which limits many practical applications. It may be that GPS and Galileo satellites supporting L5/E5A frequency transceivers are less distributed over China and can only receive a small number of GPS and Galileo satellite L5/E5A signals, which makes the positioning accuracy of dual-frequency smartphones lower than the research results of European and American scholars [26]. In addition, affected by the complex canopy of the forest, even satellites with good positions may not be able to observe the whole process, which makes the satellite have a higher position dilution of precision, resulting in reduced accuracy [38].

4.3. Availability Evaluation of Smartphone Positioning in a Forest Environment

Some scholars believe that survey-GNSS devices must be selected when the positioning accuracy is required to be better than 10 m [59]. However, the results of this study show that, in SPP mode, the average accuracy of single-frequency smartphones at 57 test points is about 10 m and that of dual-frequency smartphones is about 9 m. After correcting by PPP mode, the average accuracy of single-frequency smartphones in the forest environment (DRMS) reaches 3.7 m and that of dual-frequency smartphones is 2.9 m. The horizontal accuracy of the recreational-grade receiver is 4 m in a high-canopy-openness environment and 5 m in a medium- and low-canopy-openness environment. The horizontal accuracy of smartphones in PPP mode has been comparable to that of some recreational-grade receivers in an environment of high-canopy openness. The positioning accuracy of smartphones even shows certain advantages, which can be used as an alternative to projects with low-positioning-accuracy requirements in forestry tasks, such as under forest navigation, preliminary positioning of points of interest, and forest route planning [43]. In addition, to ensure that the positioning data of this experiment will not be interfered with by the base station's signal, all smartphones adopt flight mode for positioning observation. If the mobile communication function is enabled, AGNSS technology will play an auxiliary role in improving positioning accuracy [60,61] and the offline availability of smartphones will be further improved.

In this study, the raw data of smartphone location are modified by post-processing PPP mode. The test results show that the smartphone forest environment combined with PPP post-processing technology can achieve good location accuracy. Compared with relatively high-precision positioning methods, such as RTK, PPP technology does not require the cooperation of reference stations, so the measurement distance is not limited by base stations [62,63]. Suppose we combine the real-time PPP applications that have appeared on the Android platform, such as PPPAnd (a real-time precision single-point positioning (PPP) software on the Android platform developed by Wang et al. [64]) or the real-time precision single-point positioning software based on Android mobile terminals developed by Li et al. [65] and Guo et al. [66]. In that case, we can obtain a high level of real-time accuracy.

This study proves that smartphones, combined with modern positioning technology, have achieved a very similar accuracy level with recreational-grade receivers without differential correction in a forest and reached a positioning accuracy equivalent to that of recreational-grade receivers and older map-grade receivers. It proves that low-end receivers can be replaced by mobile intelligent devices [67]. It should be pointed out that advanced survey-grade receivers are still needed under a very dense canopy to carry out high-precision positioning [68].

5. Conclusions

This study compares the single-point positioning accuracy and PPP post-processing positioning accuracy of three smartphones (OPPO K9, Realme GT NEO, HUAWEI P50 Pro), commonly used recreational-grade GNSS devices (UniStrong G138BD), and survey-grade GNSS devices (HiTarget iRTK2). The influence of canopy openness on the number of satellites, signal quality, and positioning accuracy of GNSS devices is analyzed. The results show that:

1. The number of available satellites for dual-frequency smartphones and survey-grade receivers was significantly positively correlated with canopy openness ($p < 0.05$).

There was a significant positive correlation between canopy openness and C/N0 ($p < 0.05$).

2. The C/N0 of survey-grade receivers is significantly higher than that of smartphones. In addition to recreational-grade devices, the positioning accuracy of smartphones and survey-grade devices improves with the increase in canopy openness. However, there is a threshold value for improvements in the positioning accuracy of the device by openness.
3. In SPP mode, the horizontal accuracy of the smartphone is low. The positioning accuracy of survey-grade and recreational-grade devices in all directions is better than that of smartphones. In comparison, the positioning accuracy of dual-frequency smartphones in smartphones is better than that of single-frequency smartphones.
4. After PPP-mode correction, the positioning accuracy of smartphones is improved by 2–4-times. The positioning accuracy of smartphones in all directions is better than that of recreational-grade devices, while survey-grade devices still maintain the highest positioning accuracy. When the canopy openness is greater than 0.7, the smartphone can reach a positioning accuracy of about 2.5 m.

In general, the horizontal positioning accuracy of dual-frequency smartphones under the forest is better than that of single-frequency smartphones, which can meet the accuracy of recording the approximate location of sample plots or rough navigation in the forest environment. If such work does not require high positioning accuracy, try to choose dual-frequency full-mode smartphones. After PPP-mode correction, the smartphone can achieve a horizontal positioning accuracy of about 2.5 m in the high-canopy openness environment (>0.7), meeting the accuracy requirements of forestry setting out, resetting, and forest boundary determination. However, in a low-canopy-openness environment (<0.7) and relatively complex forest location, survey-grade GNSS devices are still required to cooperate with PPP mode or real-time differential positioning technology to obtain more accurate sub-meter-level positioning data.

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References

1. Fernandez-Prades, C.; Presti, L.L.; Falletti, E. Satellite radiolocalization from GPS to GNSS and beyond: Novel technologies and applications for civil mass market. *Proc. IEEE* **2011**, *99*, 1882–1904. [CrossRef]
2. Li, X.; Zhang, X.; Ren, X.; Fritsche, M.; Wickert, J.; Schuh, H. Precise positioning with current multi-constellation global navigation satellite systems: GPS, GLONASS, Galileo and BeiDou. *Sci. Rep.* **2015**, *5*, 1–14. [CrossRef] [PubMed]
3. Poolsin, C.; Sa-Ngiam, N.; Sutthisangiam, N. Development of Centimeter Level Positioning Mobile Based Application. In Proceedings of the 2021 23rd International Conference on Advanced Communication Technology (ICACT), PyeongChang, Korea, 7–10 February 2021; pp. 63–67.
4. Realini, E.; Caldera, S.; Pertusini, L.; Sampietro, D. Precise GNSS positioning using smart devices. *Sensors* **2017**, *17*, 2434. [CrossRef] [PubMed]
5. Schaefer, M.; Woodyer, T. Assessing absolute and relative accuracy of recreation-grade and mobile phone GNSS devices: A method for informing device choice. *Area* **2015**, *47*, 185–196. [CrossRef]

6. Dabove, P.; Di Pietra, V.; Piras, M. GNSS positioning using mobile devices with the android operating system. *ISPRS Int. J. Geo-Inf.* **2020**, *9*, 220. [CrossRef]
7. Karki, B.; Won, M. Characterizing Power Consumption of Dual-Frequency GNSS of Smartphone. In Proceedings of the GLOBECOM 2020-2020 IEEE Global Communications Conference, Taipei, Taiwan, 7–11 December 2020; pp. 1–6.
8. Wang, L.; Groves, P.D.; Ziebart, M.K. Smartphone shadow matching for better cross-street GNSS positioning in urban environments. *J. Navig.* **2015**, *68*, 411–433. [CrossRef]
9. Pesyna, K.M.; Heath, R.W.; Humphreys, T.E. Centimeter positioning with a smartphone-quality GNSS antenna. In Proceedings of the 27th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2014), Tampa, FL, USA, 8–12 September 2014; pp. 1568–1577.
10. Dabove, P.; Manzino, A.M. Accurate real-time GNSS positioning assisted by tablets: An innovative method for positioning and mapping. *GEAM Geoing. Ambient. E Min.* **2016**, *148*, 17–22.
11. Herrera, A.M.; Suhandri, H.F.; Realini, E.; Reguzzoni, M.; de Lacy, M. goGPS: Open-source MATLAB software. *GPS Solut.* **2016**, *20*, 595–603. [CrossRef]
12. Humphreys, T.E.; Murrian, M.; Van Diggelen, F.; Podshivalov, S.; Pesyna, K.M. On the feasibility of cm-accurate positioning via a smartphone's antenna and GNSS chip. In Proceedings of the 2016 IEEE/ION Position, Location and Navigation Symposium (PLANS), Savannah, GA, USA, 11–14 April 2016; pp. 232–242.
13. Fortunato, M.; Critchley-Marrows, J.; Siutkowska, M.; Ivanovici, M.L.; Benedetti, E.; Roberts, W. Enabling high accuracy dynamic applications in urban environments using PPP and RTK on android multi-frequency and multi-GNSS smartphones. In Proceedings of the 2019 European navigation conference (ENC), Warsaw, Poland, 9–12 April 2019; pp. 1–9.
14. Robustelli, U.; Baiocchi, V.; Pugliano, G. Assessment of dual frequency GNSS observations from a Xiaomi Mi 8 Android smartphone and positioning performance analysis. *Electronics* **2019**, *8*, 91. [CrossRef]
15. Wu, Q.; Sun, M.; Zhou, C.; Zhang, P. Precise point positioning using dual-frequency GNSS observations on smartphone. *Sensors* **2019**, *19*, 2189. [CrossRef]
16. Yan, L.; Qi, X.; Yang, J.Z.; Qiu, M.L.; Cai, J.Z. Key Technologies Analysis and Market Status of High Precision Positioning Based on Mobile Phone. In Proceedings of the China Satellite Navigation Conference, Chengdu, China, 23–25 May 2020; pp. 288–297.
17. Liu, Y.; Gao, C.; Chen, B.; Zhang, R. Pseudo-range single point and differential positioning accuracy test based on android smartphone. In Proceedings of the China Satellite Navigation Conference, Beijing, China, 22–25 May 2019; pp. 72–81.
18. Warnant, R.; Vyvere, D.; Van, L.; Warnant, Q. Positioning with single and dual frequency smartphones running Android 7 or later. In Proceedings of the 31st international technical meeting of the satellite division of the Institute of Navigation (ION GNSS+ 2018), Miami, FL, USA, 24–28 September 2018; pp. 284–303.
19. Chen, B.; Gao, C.; Liu, Y.; Sun, P. Real-time precise point positioning with a Xiaomi MI 8 android smartphone. *Sensors* **2019**, *19*, 2835. [CrossRef]
20. Danskin, S.; Bettinger, P.; Jordan, T. Multipath mitigation under forest canopies: A choke ring antenna solution. *For. Sci.* **2009**, *55*, 109–116.
21. McGaughey, R.J.; Ahmed, K.; Andersen, H.-E.; Reutebuch, S.E. Effect of occupation time on the horizontal accuracy of a mapping-grade GNSS receiver under dense forest canopy. *Photogramm. Eng. Remote Sens.* **2017**, *83*, 861–868. [CrossRef]
22. Smyrnaios, M. *Carrier-Phase Multipath in Satellite-Based Positioning*; Leibniz Universität Hannover: Hannover, Germany, 2016.
23. Valbuena, R.; Mauro, F.; Rodriguez-Solano, R.; Manzanera, J. Accuracy and precision of GPS receivers under forest canopies in a mountainous environment. *Span. J. Agric. Res.* **2010**, *8*, 1047–1057. [CrossRef]
24. Merry, K.; Bettinger, P. Smartphone GPS accuracy study in an urban environment. *PLoS ONE* **2019**, *14*, e0219890. [CrossRef]
25. Piedallu, C.; Gégout, J.-C. Effects of forest environment and survey protocol on GPS accuracy. *Photogramm. Eng. Remote Sens.* **2005**, *71*, 1071–1078. [CrossRef]
26. Rodríguez Pérez, J.R.; Álvarez Taboada, M.F.; Sanz Ablanedo, E.; Gavela, A. Comparison of GPS Receiver Accuracy and Precision in Forest Environments. Practical Recommendations Regarding Methods and Receiver Selection. In Proceedings of Shaping the Change XXIII FIG Congress, Munich, Germany, 8–13 October 2006.
27. Galán, C.O.; Rodríguez-Pérez, J.R.; Torres, J.M.; Nieto, P.G. Analysis of the influence of forest environments on the accuracy of GPS measurements by using genetic algorithms. *Math. Comput. Model.* **2011**, *54*, 1829–1834. [CrossRef]
28. Hasegawa, H.; Yoshimura, T. Application of dual-frequency GPS receivers for static surveying under tree canopies. *J. For. Res.* **2003**, *8*, 0103–0110. [CrossRef]
29. Yoshimura, T.; Hasegawa, H. Comparing the precision and accuracy of GPS positioning in forested areas. *J. For. Res.* **2003**, *8*, 147–152. [CrossRef]
30. Mori, A. Accuracy and efficiency of DGPS inside the forest-the effects of tree stem and crown on accuracy of positioning. *Appl. Sci.* **2000**, *9*, 13–17.
31. Kobayashi, H.; Yada, Y.; Chachin, T.; Okano, K.; Nogami, Y.; Torimoto, H. Evaluation of GPS receivers' performance inside and outside forests. *J. Jpn. For. Soc.* **2001**, *83*, 135–142.
32. Sawaguchi, I.; Nishida, K.; Shishiuchi, M.; Tatsukawa, S. Positioning precision and sampling number of DGPS under forest canopies. *J. For. Res.* **2003**, *8*, 0133–0137. [CrossRef]
33. Deckert, C.; Bolstad, P.V. Forest canopy, terrain, and distance effects on global positioning system point accuracy. *Photogramm. Eng. Remote Sens.* **1996**, *62*, 317–321.

34. Hansen, M.C.; Riggs, R.A. Accuracy, precision, and observation rates of global positioning system telemetry collars. *J. Wildl. Manag.* **2008**, *72*, 518–526. [CrossRef]
35. Næsset, E. Point accuracy of combined pseudorange and carrier phase differential GPS under forest canopy. *Can. J. For. Res.* **1999**, *29*, 547–553. [CrossRef]
36. Sawaguchi, I.; Saitoh, Y.; Tatsukawa, S. A study of the effects of stems and canopies on the signal to noise ratio of GPS signals. *J. For. Res.* **2005**, *10*, 395–401. [CrossRef]
37. Naesset, E.; Jonmeister, T. Assessing point accuracy of DGPS under forest canopy before data acquisition, in the field and after postprocessing. *Scand. J. For. Res.* **2002**, *17*, 351–358. [CrossRef]
38. Bettinger, P.; Merry, K.; Bayat, M.; Tomaštík, J. GNSS use in forestry–A multi-national survey from Iran, Slovakia and southern USA. *Comput. Electron. Agric.* **2019**, *158*, 369–383. [CrossRef]
39. Dabove, P.; Di Pietra, V. Towards high accuracy GNSS real-time positioning with smartphones. *Adv. Space Res.* **2019**, *63*, 94–102. [CrossRef]
40. Bianchi, S.; Cahalan, C.; Hale, S.; Gibbons, J.M. Rapid assessment of forest canopy and light regime using smartphone hemispherical photography. *Ecol. Evol.* **2017**, *7*, 10556–10566. [CrossRef]
41. Vastaranta, M.; González Latorre, E.; Luoma, V.; Saarinen, N.; Holopainen, M.; Hyyppä, J. Evaluation of a smartphone app for forest sample plot measurements. *Forests* **2015**, *6*, 1179–1194. [CrossRef]
42. Tomaštík, J., Jr.; Tomaštík, J., Sr.; Saloň, Š.; Piroh, R. Horizontal accuracy and applicability of smartphone GNSS positioning in forests. *For. Int. J. For. Res.* **2017**, *90*, 187–198. [CrossRef]
43. Tomaštík, J.; Chudá, J.; Tunák, D.; Chudý, F.; Kardoš, M. Advances in smartphone positioning in forests: Dual-frequency receivers and raw GNSS data. *For. Int. J. For. Res.* **2021**, *94*, 292–310. [CrossRef]
44. Guo, Y. Positioning accuracy evaluation of smart phones in secondary forests of Poplar and Birch with different canopy openness. *Hebei Agric. Univ. China* **2021**, *16*, 1–61.
45. Zhang, Y.; Fang, H.; Ma, L.; Ye, Y.; Wang, Y. Estimation of forest leaf area index and clumping index from the Global Positioning System (GPS) satellite carrier-to-noise-density ratio (C/N0). *Remote Sens. Lett.* **2020**, *11*, 146–155. [CrossRef]
46. Wright, W.; Wilkinson, B.; Cropper, W., Jr. Development of a GPS forest signal absorption coefficient index. *Forests* **2018**, *9*, 226. [CrossRef]
47. Holden, N.; Martin, A.; Owende, P.; Ward, S. A method for relating GPS performance to forest canopy. *Int. J. For. Eng.* **2001**, *12*, 51–56. [CrossRef]
48. Kaartinen, H.; Hyyppä, J.; Vastaranta, M.; Kukko, A.; Jaakkola, A.; Yu, X.; Pyörälä, J.; Liang, X.; Liu, J.; Wang, Y. Accuracy of kinematic positioning using global satellite navigation systems under forest canopies. *Forests* **2015**, *6*, 3218–3236. [CrossRef]
49. Liu, W.; Shi, X.; Zhu, F.; Tao, X.; Wang, F. Quality analysis of multi-GNSS raw observations and a velocity-aided positioning approach based on smartphones. *Adv. Space Res.* **2019**, *63*, 2358–2377. [CrossRef]
50. Bu, J.-W.; Li, X.-L.; Zuo, X.-Q.; Chang, J.; Li, X.-M. Quality comparison and analysis of Beidou/GPS/GLONASS multi system satellite positioning data. *Prog. Geophys.* **2018**, *33*, 1–9.
51. Li, Y.; Liu, L.; Cui, L.; Huang, L.; Zhao, Z.; Huang, X. Effects of canopy openness on positioning availability and initialization time of GNSS RTK in forests. *Sci. Silvae Sin.* **2014**, *50*, 78–84.
52. Wing, M.G.; Eklund, A. Performance comparison of a low-cost mapping grade global positioning systems (GPS) receiver and consumer grade GPS receiver under dense forest canopy. *J. For.* **2007**, *105*, 9–14.
53. Sigrist, P.; Coppin, P.; Hermy, M. Impact of forest canopy on quality and accuracy of GPS measurements. *Int. J. Remote Sens.* **1999**, *20*, 3595–3610. [CrossRef]
54. Szot, T.; Specht, C.; Specht, M.; Dabrowski, P.S. Comparative analysis of positioning accuracy of Samsung Galaxy smartphones in stationary measurements. *PLoS ONE* **2019**, *14*, e0215562. [CrossRef] [PubMed]
55. Pang, L.; Huang, S.; Li, W.; Tang, X. Application of GNSS in forestry sector in China. *World For. Res.* **2019**, *32*, 41–46.
56. Robustelli, U.; Baiocchi, V.; Marconi, L.; Radicioni, F.; Pugliano, G. Precise Point Positioning with Single and Dual-Frequency Multi-GNSS Android Smartphones. In Proceedings of the CEUR Workshop Proceeding, Vienna, Austria, 3–6 November 2020.
57. Paziewski, J. Recent advances and perspectives for positioning and applications with smartphone GNSS observations. *Meas. Sci. Technol.* **2020**, *31*, 091001. [CrossRef]
58. Aggrey, J.; Bisnath, S.; Naciri, N.; Shinghal, G.; Yang, S. Multi-GNSS precise point positioning with next-generation smartphone measurements. *J. Spat. Sci.* **2020**, *65*, 79–98. [CrossRef]
59. Hong-gan, W.; Peng, L.; Yun-feng, Y.; Ji-hui, X.; Heng, Z. Comparison on Multimodal Positioning Accuracy of Commercial and Professional Receiver in Forest Environment. *For. Sci. Res.* **2020**, *33*, 170–176.
60. Jingxue, B.; Jie, Z.; Ying, G. Accuracy of GPS and A-GPS positioning on Android phone. *Bull. Surv. Mapp.* **2016**, *7*, 10.
61. Van Diggelen, F.S.T. *A-Gps: Assisted Gps, Gnss, and Sbas*; Artech House: Boston, MA, USA; London, UK, 2009.
62. Xiaohong, Z.; Xingxing, L.; Pan, L. Review of GNSS PPP and its application. *Acta Geod. Cartogr. Sin.* **2017**, *46*, 1399.
63. Ningsong, H.; Wentao, F.; Shengfeng, G.; Yidong, L. Precise positioning of smartphones and results analysis. *Bull. Surv. Mapp.* **2020**, *1*, 5–9.
64. Liang, W.; Zishen, L.; Kai, Z.; Shaotian, Z.; Hong, Y. Multi-GNSS real-time un-differenced precise positioning for Android smart devices. *Navig. Position. Timing* **2019**, *6*, 1–10.

65. Li, J.; Zheng, Z.; Zhang, D. Research on real-time BDS/GPS single-frequency PPP technology for Android mobile terminal. *Sci. Surv. Mapp.* **2019**, *44*, 149–153.
66. Guo, F.; Wu, W.; Zhang, X.; Liu, W. Realization and Precision Analysis of Real-time Precise Point Positioning with Android Smartphones. *J. Wuhan Univ. Inf. Sci. Ed.* **2021**, *46*, 1053–1062.
67. Lee, T.; Bettinger, P.; Cieszewski, C.J.; Gutierrez Garzon, A.R. The applicability of recreation-grade GNSS receiver (GPS watch, Suunto Ambit Peak 3) in a forested and an open area compared to a mapping-grade receiver (Trimble Juno T41). *PLoS ONE* **2020**, *15*, e0231532. [CrossRef]
68. Drosos, V.C.; Malesios, C. Measuring the accuracy and precision of the Garmin GPS positioning in forested areas: A case study in Taxiarchis-Vrastama University Forest. *J. Environ. Sci. Eng. B* **2012**, *2012*, 566–576.