THE PERFORMANCE ANALYSIS OF BDS POSITIONING IN NORDIC AREAS BASED ON THE SMARTPHONE

Chen Chen [1], Yuwei Chen[2] *, Changhui Jiang [2], Yuming Bo[1] Jianxin Jia[2], Haibin Sun[2], Zhe He[3]

[1] School of Automation, Nanjing University of Science and Technology, Nanjing, 210094, China – (chenchen115039,byming)@njust.edu.cn
[2] Department of Remote Sensing and Photogrammetry, Finnish Geospatial Research Institute, FI-02431 Kirkkonummi, Finland - （yuwei.chen, changhui.jiang, jianxin.jia） @nls.fi, sunhaibin007@gmail.com
[3] Department of Geomatics Engineering, University of Calgary, 2500 University Dr NW, Calgary, Canada - hezhe310@gmail.com

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ABSTRACT:

Nowadays, the Global Navigation Satellite System (GNSS) is widely used in many applications. As a new system, China's BeiDou navigation system (BDS) is emerging in recent years. The last satellite of the third generation global BeiDou navigation system (BDS-3) has been successfully launched on June 23 in 2020, which means that BDS can offer navigation services worldwide. We evaluate the quality of BDS signals and analyze the performance of BDS positioning based on the smartphone in Espoo, Finland. The static and kinematic experiments were implemented in the parking lot of the Finish Geospatial Research Institute (FGI) and a highway route in Espoo, respectively. Experimental results show that BDS has good satellite visibility and geometric distribution. The signal carrier-to-noise density ratio (C/N0) of BDS-2 reaches 34.22 dB-Hz, which is comparable to the Global Positioning System (GPS). However, the signal carrier-to-noise density of BDS-3 is slightly lower than BDS-2, which is due to the significant number of BDS-3 satellites at low elevation angles. The horizontal precision of BDS positioning in the static and kinematic experiment is comparable to GPS in the east direction and slightly inferior to GPS in the north direction. However, the BDS shows poor precision in the up direction. In addition, the integration of BDS with other GNSS systems can significantly improve the positioning precision. This study intends to provide a reference for further research on the BDS global Positioning, Navigation, and Timing (PNT) services, particularly for LBS and smartphone positioning.

1. INTRODUCTION

The positioning has enormous influences on human’s daily life. Fast and accurate location information acquisition becomes more and more important since more and more applications in our daily life involve location information (Y. Chen et al., 2010; Kuusniemi, H et al., 2012). With the rapid development of mobile internet technology, smart devices are playing increasingly important roles in location-based services (LBS) (L. Pei et al., 2012; W. Chen et al., 2011). Especially after 2016, when Google announced that Global Navigation Satellite System (GNSS) raw observations are available for the Android operating system starting from version 7.0, GNSS positioning based on the smartphone becomes a popular research trend.

The modernization of GNSS is a significant factor that influences the development of high-accuracy mobile positioning. As traditional satellite navigation systems, Global Positioning System (GPS), Galileo navigation satellite system (Galileo), and GLONASS have successfully operated for many years. There have been a variety of studies based on them (J. Paziewski 2020). Different from these traditional systems, China's Bei Dou navigation system (BDS) is emerging in recent years. Until 2012, the BDS has evolved from the demonstration navigation satellite system (BDS-1) to the regional navigation satellite system (BDS-2). And the last satellite of the third generation global BeiDou navigation system (BDS-3) has been successfully launched on June 23 in 2020, which marked the complete deployment of the BDS global constellation. Since then, the BDS can offer navigation services from the Asia–Pacific region to the rest of the world. With the development of the BDS, various scholars focus on using this notable system and new signals for positioning. However, there are still few studies on smartphone positioning based on the BDS, especially outside the Asia–Pacific region (R. Zou et al., 2016).

This paper conducts a systematic analysis of BDS positioning based on the smartphone in Nordic areas (Espoo, Helsinki) since the global coverage of the BDS. In this paper, we will introduce the experiment design and the data collection process. Then we analyze and assess the quality of the smartphone BDS observations, including the carrier-to-noise density ratio, the dilution of precision (DOP), the number of tracked satellites, etc. Finally, the performance of smartphone BDS single-point positioning both in static and kinematic situations are analyzed. And all the experimental results will be compared with the results of GPS/Galileo/GLONASS. This study intends to provide a reference for further research on the BDS global Positioning, Navigation, and Timing (PNT) services, particularly for LBS and smartphone positioning.

2. GNSS DATA COLLECTION

We conduct static and kinematic experiments in the Finish Geospatial Research Institute (FGI) and the areas in Espoo, respectively. The Huawei mate40 pro is used to collect the static and kinematic data of BDS/GPS/Galileo/GLONASS with an Android app GEO++RINEX. The sampling interval is one

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* Corresponding author

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second. The observed data was stored on the phone in RINEX 3.03 format. Figure.1 shows the scenes and the equipment of the static and kinematic experiments.

(a) (b)

Figure 1. The scenes and the equipment of the static and kinematic experiments. (a) is used for the static experiment. (b) is used for the kinematic experiment.

PRN	Common Name	Int. Sat. ID	Orbit
C02	BDS-2 GEO-6	2012-059A	80.3°E
C05	BDS-2 GEO-5	2010-036A	58.75°E
C08	BDS-2 IGSO-3	2011-013A	~117°E
C13	BDS-2 IGSO-6	2016-021A	~94°E
C14	BDS-2 MEO-5	2012-050B	between slots B-3 and B-4
C21	BDS-3 MEO-3	2018-018B	Slot B-5
C27	BDS-3 MEO-7	2018-003A	Slot A-4
C28	BDS-3 MEO-8	2018-003B	Slot A-5
C30	BDS-3 MEO-10	2018-029B	Slot A-3
C33	BDS-3 MEO-14	2018-072B	Slot B-3
C36	BDS-3 MEO-17	2018-093A	Slot C-4
C37	BDS-3 MEO-18	2018-093B	Slot C-6
C38	BDS-3 IGSO-1	2019-023A	~110.5°E
C42	BDS-3 MEO-20	2019-090B	Moving to Slot B-4
C43	BDS-3 MEO-21	2019-078B	Slot A-6
C46	BDS-3 MEO-24	2019-061A	Slot C-5

Table 1. The information of BDS satellites tracked by Huawei mate40 pro.

The static experiment is implemented in the parking lot in FGI. As shown in Figure 1(a), an experimental box designed by ourselves, which can offer the Real-Time Kinematic (RTK) results as the reference, is placed in an open scenario and collect the data during the static experiment. The smartphone is placed on the experimental box in its natural state to log the GNSS data for one hour (13:22:22-14:22:24 UTC). The raw data collected by the experimental box is stored on the computer. After processing, we can obtain the RTK results, whose accuracy can reach centi-meter level, as the reference for the GNSS single-point positioning based on the smartphone.

The kinematic experiment is implemented in complex Sbds-3cenes. As shown in Figure 1(b), we use the Novatel antenna fixed on the top of the vehicle to collect the GPS data, which is used to obtain the RTK trajectory as the reference. The smartphone is held by the tester in the vehicle beside the window to collect the GNSS data. Then we drive the vehicle in Espoo to collect GNSS data for 15 minutes (15:13:50-15:28:50 UTC). The route of the driving experiment is designed in advance, which contains challenging environments for GNSS positioning. The experimental route includes different scenes such as buildings, tunnels, trees, etc, where the GNSS signals are degraded or even denied.

As the test smartphone, the Huawei mate40 pro can receive satellite signals from GPS, QZSS, Galileo, GLONASS, and BDS. In the static experiment, 10 BDS satellites are tracked. Table 1 shows the details of BDS satellites tracked by Huawei mate40 pro in the static experiments. The sky plot of the observed satellites for one hour in the static experiment is shown in Figure 2. According to Figure 2, GPS shows the best visibility and Galileo the worst. The visibility of these constellations shown in Figure 3 also demonstrates that the signals of Galileo are the worst of these four satellite systems. Table 1 shows the details of the BDS satellites tracked by the smartphone during the static experiment. For BDS-3, C27~C28, C36~C38, and C46 show better observation conditions during the static experiment.

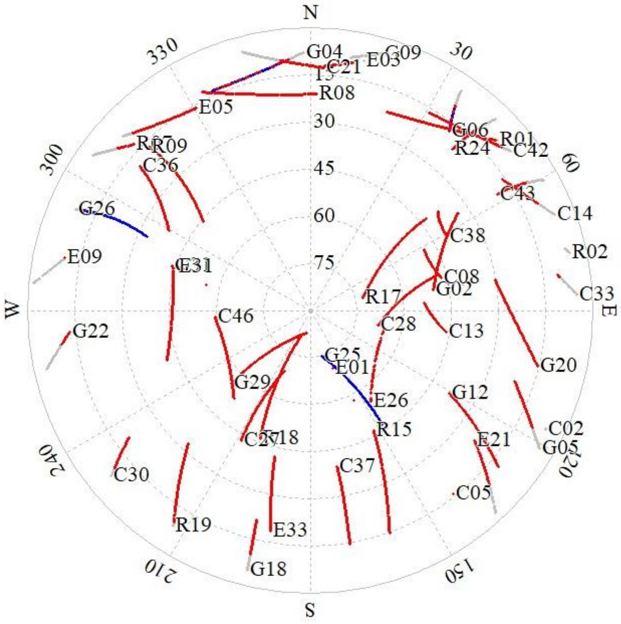

Figure 2. The sky plot of the observed satellites for one hour.

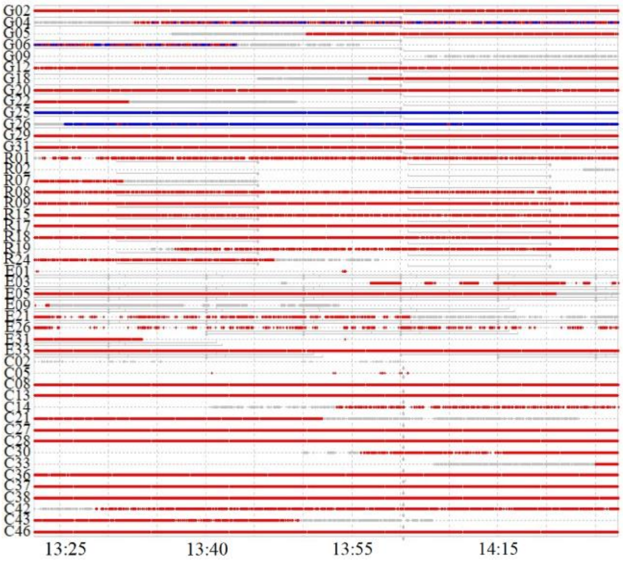

Figure 3. The satellite visibility for one hour.

In the rest of the paper, we evaluate the quality of the BDS data based on the static observations and the BDS positioning performance both in the static and the kinematic situations. In addition to BDS, the data of other constellations are also analyzed as a comparison.

3. SMARTPHONE BDS OBSERVATION QUALITY ANALYSIS

In this section, we evaluate the quality of the BDS singles based on the static observations. The evaluation includes the Signal-to-Noise Ratio (SNR), the number of satellites tracked by the smartphone, and the DOP. The results of BDS are compared with other constellations.

3.1 Carrier-to-noise density ratio

The carrier-to-noise ratio (C/N0) is an important indicator of the signal quality of global navigation satellite systems It is the normalized expression of SNR, which means the ratio of the signal power
to the noise power density (S. Liu et al., 2022). In a vector receiver, C/N0 can be used as a priori information to determine the validity of the observations and estimate the observation noise. The higher C/N0 indicates the better quality of GNSS signals.

Generally, the C/N0 measurements of a smartphone are lower than that of geodetic-grade equipment. Figure 4 shows the variation trend of C/N0 of different satellites on BDS B1, GPS L1, Galileo E1, E5a, and GLONASS G1 at different times and elevation angles. It can be seen that the C/N0 value has a positive correlation with the elevation angle of the satellite. According to the colour bar, we can see that GPS singles perform the best at high elevation angles and Galileo signals perform the worst.

To further analyze the C/N0 of BDS, especially the comparison between BDS-2 and BDS-3, we count the C/N0 measurements of the satellites and calculated their mean values and standard deviations (STD). The results are shown in Table 2 and Table 3. The average C/N0 of BDS reaches 30.63dB-Hz, which is lower than GPS but higher than Galileo and GLONASS. Table 2 also shows the respective C/N0 statistics of the two subsystems of BDS. However, its standard deviation of 9.69 dB-Hz is higher than GPS and Galileo. This is partly due to the inconsistent C/N0 measurements between satellites at high and low elevation angles. According to the elevation angles of different BDS satellites listed in Table 2, it can be seen that the satellites at angles lower than 20°, especially lower than 10°, have smaller C/N0 values.

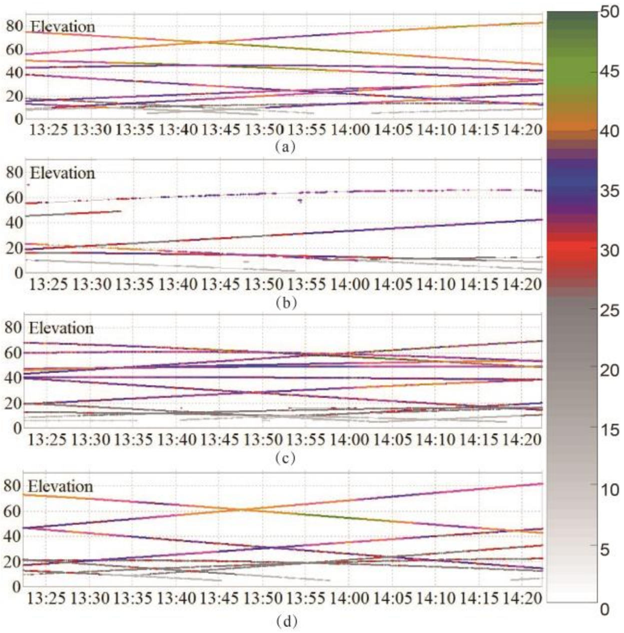

Figure 4. The variation trend of C/N0 of GPS, Galileo, BDS, and GLONASS at different times and elevation angles. (a) is the variation trend of C/N0 of GPS. (b) is the variation trend of C/N0 of Galileo. (c) is the variation trend of C/N0 of BDS. (d) is the variation trend of C/N0 of GLONASS. The colour bar indicates the level of the C/N0 value.

3.2 Dilution of precision

In GNSS navigation and positioning, we use the DOP to evaluate the effect of the observed satellites' spatial geometry distribution on positioning accuracy. Generally, the better the distribution of satellites in the sky, the higher the positioning accuracy (Y. Wang et al., 2022). That means, higher DOP values indicate weak

Constellation	C/N0	
	Mean (dB-Hz)	STD (dB-Hz)
BDS	30.63	9.69
GPS	35.16	8.20
Galileo	26.99	7.32
GLONASS	30.19	9.97

Table 2. The mean values and standard deviations of C/N0 measurements of different satellites.

Constellation			Elevation angle(°)	C/N0	
				Mean (dB-Hz)	STD (dB-Hz)
BDS	BDS-2	C02	6.2~6.4	26.39	2.69
		C05	16.1~16.3	26.36	3.15
		C08	47.1~48.9	36.18	2.20
		C13	46.2~53.7	38.66	3.61
	BDS-3	C14	6.7~16.2	13.06	4.21
		C21	12.8~5.1	16.44	4.49
		C27	43.3~69.3	36.39	5.15
		C28	67.9~74.7	36.19	8.15
		C30	7.8~20.1	23.98	5.43
		C33	5.1~10.7	17.62	4.01
		C36	19.2~38.7	35.81	4.95
		C37	39.8~14.6	30.82	5.61
		C38	40.6~38.5	32.03	4.34
		C42	8.6~16.7	16.49	4.10
		C43	19.9~5.1	17.49	4.64
		C46	59.7~53.1	37.56	2.85
	BDS-2		/	34.22	8.81
	BDS-3		/	29.66	9.70

Table 3. The mean values and standard deviations of C/N0 measurements of BDS.

satellite geometry and a low probability of high accuracy. DOP falls into the following categories: geometric dilution of precision (GDOP), position dilution of precision (PDOP), horizontal dilution of precision (HDOP), and vertical dilution of precision (VDOP). Table 4 illustrates the DOP values for each constellation during the one-hour static experiment. Figure 4 illustrates the number of tracked satellites with elevation angles above 10° for each constellation during the one-hour experiment. According to Figure 4, GPS has the best visibility in the static situation as over 8 visible satellites for most of the time. BDS has over 5 visible satellites for most of the time. Galileo has the smallest number of visible satellites. For over 80% of the time, the number of tracked satellites of Galileo is less than 4, which will definitely influence the positioning performance of Galileo despite its better DOP values. The ascending order of the overall GDOP value is GPS, Galileo, BDS, and GLONASS, and their average GDOP is 2.1, 2.1,3.3 and 3.3, respectively. It can be seen that GPS and BDS shows the best distribution of satellites in the sky.

Constellation	GDOP	PDOP	HDOP	VDOP
GPS	2.1	1.9	1.1	1.6
BDS	2.1	1.9	1.0	1.6
Galileo	3.3	3.1	1.7	2.5
GLONASS	3.3	2.9	1.5	2.4

Table 4. The average DOP of different constellations during the one-hour static experiment.

Figure 5 illustrates the number of tracked satellites for each constellation during the one-hour static observation period. It can be seen that BDS satellites have the best visibility during the one-hour observation period. GPS is in the second. Galileo has the smallest number of tracked satellites. For most of the time, the number of tracked satellites of Galileo is less than 4. That is, Galileo cannot realize the positioning during the static experiment, despite its good distribution.

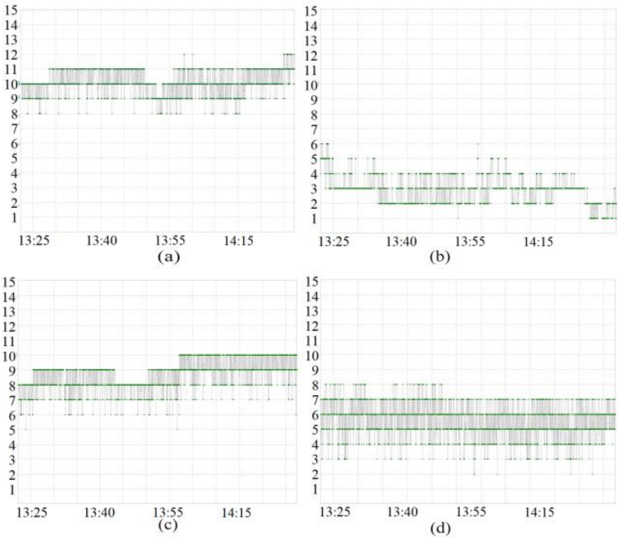

Figure 5. The tracked satellites' number of different constellations with elevation angles above 10° during the one-hour static experiment. (a) is the number of tracked satellites for BDS. (b) is the number of tracked satellites for Galileo. (c) is the number of tracked satellites for GPS. (d) is the number of tracked satellites for GLONASS.

4. EVALUATION OF BDS POSITIONING PERFORMANCE BASED ON THE SMARTPHONE

In this section, we evaluated the BDS positioning performance based on the smartphone utilizing the pseudo-range observations. At the same time, the positioning results of other systems are used for contrastive analysis. The RTK results are also involved in the evaluation.

4.1 Static positioning performance evaluation

As we mentioned above, although the distribution of Galileo satellites performs well with the GDOP value 3.3, the number of tracked satellites is less than 4 the most of time during the observation period. That is, Galileo cannot be used for the single-point positioning in the static experiment. In this section, we make comparisons of single-point positioning results between GPS, BDS, GLONASS, and their combinations. The RTK result is used as the ground truth. The elevation cut-off angle of the satellite is set to 10° for static experiment and 10° for static experiment and kinematic experiment.

Figure 6 shows the horizontal positioning results obtained by the pseudo-range observations of different systems and their combinations. The average value of RTK results during the one-hour period is selected as the original point of the east-north-up (ENU) coordinate system. Figure 7 shows the details of positioning deviations in the three directions. Table 5 shows the standard deviations and the root mean square errors (RMSE) of the smartphone positioning in the east, north, and up directions. It is clearly seen that GLONASS has the worst positioning results due to its inconsistent ranging precision and inter-frequency code bias. In contrast, there are much better concentrations of BDS and GPS positioning results. The positioning precision of BDS and GPS in the east direction is better than that in the north direction. The positioning precision of BDS in the up direction is obviously worse than GPS, which may cause by the unsatisfactory BDS-3 signals in Nordic areas in this observation period. The observation period which is too short in this experiment. According to Figure 6 and Table 5, the fusion of BDS B1, GPS L1, and GLONASS G1 code observations significantly improve the positioning accuracy, which is due to the increase of valid satellites and the enhancement of geometric distribution of satellites. Meanwhile, the concentration of the GPS/BDS/GLONASS positioning is higher. There are no obvious outlying points for this positioning solution. That is, the multiple systems can improve positioning performance.

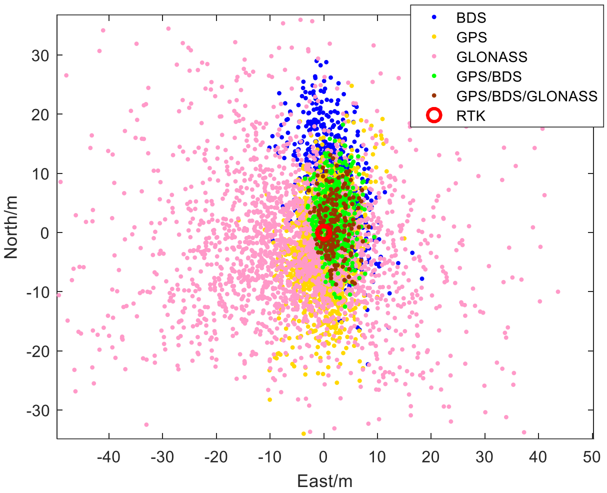

Figure 6. Static smartphone positioning results based on BDS and GPS satellite systems and their combination. The blue points are the single-point positioning results of BDS. The yellow points are the single-point positioning results of GPS. The pink points are the single-point positioning results of GLONASS. The green points are the single-point positioning results of the combination of GPS and BDS. The brown points are the single-point positioning results of the combination of GPS, BDS, and GLONASS. The red circle is the average RTK result of the one-hour static experiment.

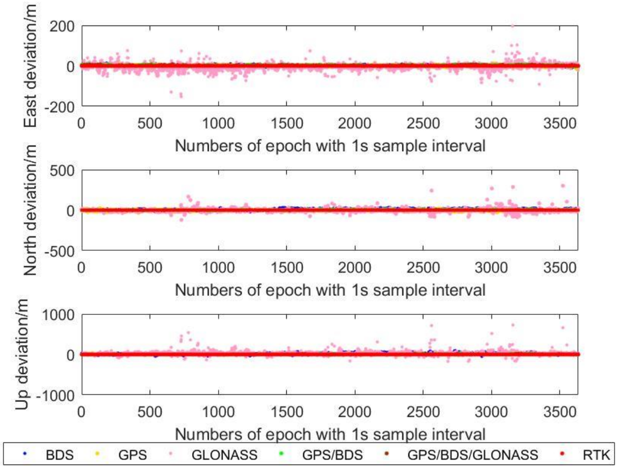

Figure 7. Static smartphone positioning deviations in the east, north, and up directions based on BDS and GPS satellite systems and their combination. The blue points are the single-point positioning results of BDS. The yellow points are the single-point positioning results of GPS. The pink points are the single-point positioning results of GLONASS. The green points are the single-point positioning results of the combination of GPS and, BDS. The brown points are the single-point positioning results of the combination of GPS, BDS and GLONASS. The red points are the RTK results of the one-hour static experiment.

Constellation	STD(m)			RMSE(m)		
	East	North	Up	East	North	Up
GPS	3.05	6.29	7.39	3.07	6.47	7.39
BDS	3.45	8.06	21.70	3.45	8.06	21.69
GLONASS	18.35	20.76	51.05	18.35	20.75	51.07
GPS/BDS	2.17	5.15	8.15	2.17	5.15	8.14
GPS/BDS/Galileo	2.09	4.67	8.56	2.09	4.66	8.53
GPS/BDS/ GLONASS	1.97	3.92	7.48	1.95	3.88	7.40

Table 5. Statistical results of smartphone static positioning deviation.

4.2 Kinematic positioning performance evaluation

Figure 8 shows the ground truth of the kinematic car-borne experiment in Espoo. As shown in Figure 1(b), The trajectory is the RTK results collected by the Novatel antenna on the top of the vehicle. The kinematic experiment is conducted in urban areas of Espoo. The experimental route contains different scenes including highways, tunnels, buildings, etc. The sky plot of the observed satellites for the kinematic car-borne experiment is shown in Figure 9.

The satellite visibility and the number of satellites tracked by Huawei mate40 pro during the kinematic car-borne experiment are illustrated in Figure 10 and Figure 11, respectively. Note that only the satellites with elevation angles above 10° are taken into account. According to the results, the numbers of tracked satellites for BDS and GPS are significantly larger than GLONASS and Galileo. For most of the time, the number of tracked satellites for GPS is over 8. The number of tracked satellites for BDS is over 10. In the contrast, the number of tracked satellites for Galileo is around 4 most of the time. Although only four satellites are needed in positioning, the poor stability and continuity of the tracked satellites significantly influence the positioning performance of Galileo. That is, the same as the static experiment, Galileo cannot realize the smartphone positioning during the kinematic car-borne experiment. In this part, we analyze the positioning performance of BDS, GPS, GLONASS, and their combinations.

The kinematic smartphone positioning results based on BDS, GPS, GLONASS, and their combination are illustrated in Figure 12. To clearly see the differences in positioning results between BDS, GPS, and GLONASS satellite systems and their combinations, Figure 12(a) and Figure 12(b) are highlighted. GLONASS performs the worst in the kinematic positioning. GDS and GPS positioning results can follow the trajectory of RTK much better than GLONASS. the results of multiple systems, especially the combination of BDS, GPS, and GLONASS, show the best concentration and positioning precision in the kinematic smartphone positioning.

Figure 8. The ground truth of the kinematic car-borne experiment in Espoo. The red line indicates the real trajectory of the vehicle during the kinematic car-borne experiment.

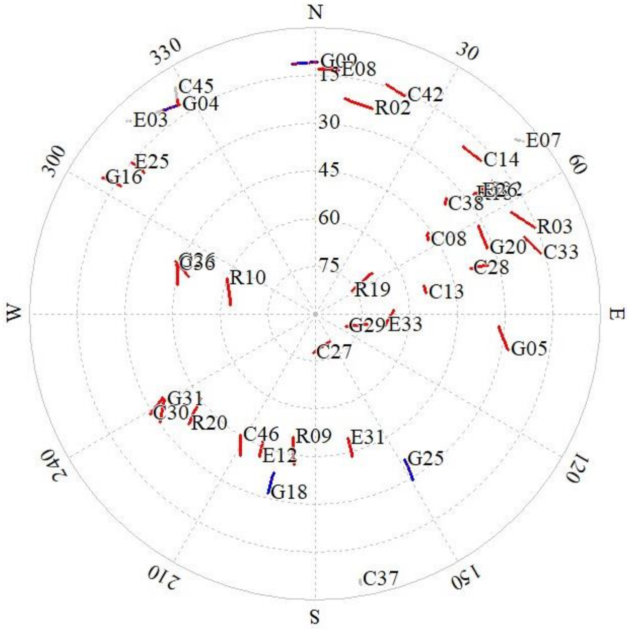

Figure 9. The sky plot of the observed satellites for the kinematic car-borne experiment.

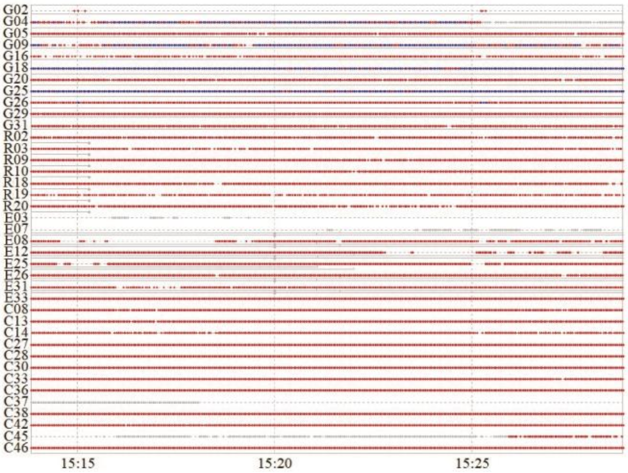

Figure 10. The satellite visibility for the kinematic car-borne experiment.

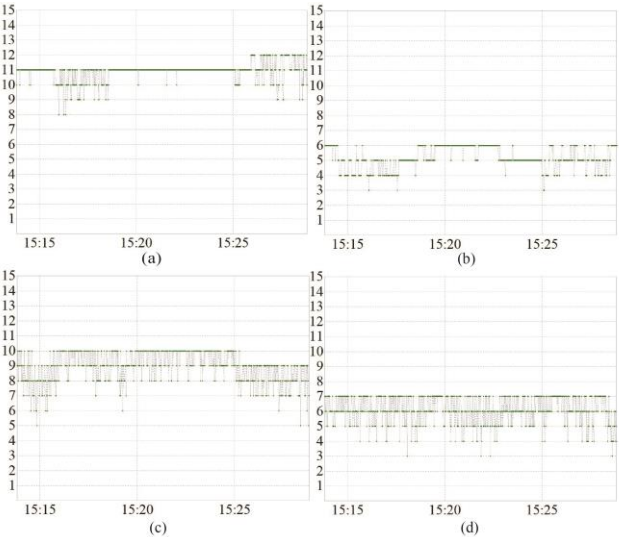

Figure 11. The tracked satellites' number of different constellations with elevation angles above 10° during the kinematic car-borne experiment. (a) is the number of tracked satellites for BDS. (b) is the number of tracked satellites for Galileo. (c) is the number of tracked satellites for GPS. (d) is the number of tracked satellites for GLONASS.

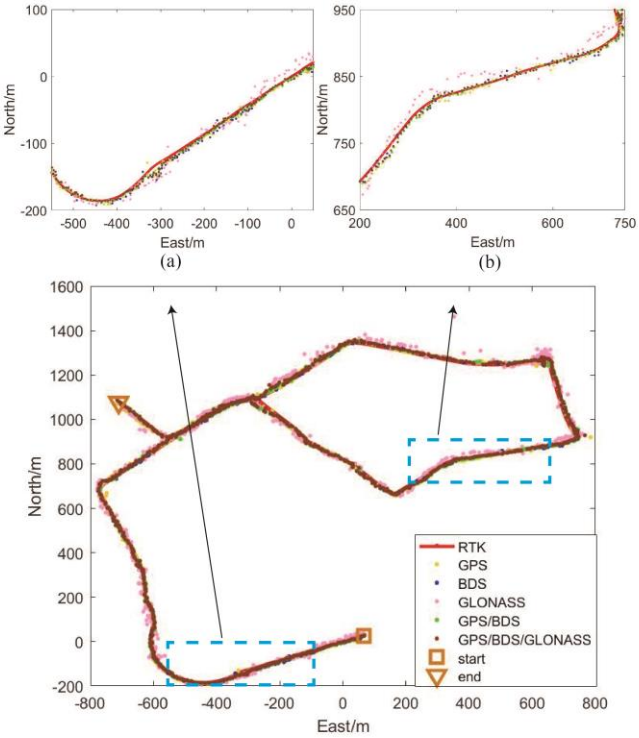

Figure 12. Kinematic smartphone positioning results based on BDS, GPS, GLONASS satellite systems and their combinations. The blue points are the single-point positioning results of BDS. The yellow points are the single-point positioning results of GPS. The pink points are the single-point positioning results of GLONASS. The green points are the-single-point positioning results of the combination of GPS and BDS. The brown points are the single-point positioning results of the combination of GPS, BDS, and GLONASS. The red points are the RTK results of the kinematic car-borne experiment. The yellow square sign is the starting point of the trajectory during the kinematic experiment. The yellow triangle is the end of the trajectory during the kinematic experiment. Two fragments marked by blue boxes are zoomed in to show the differences in positioning results between BDS, GPS, and GLONASS satellite systems and their combinations.

5. CONCLUSION

To analyze the performance of BDS smartphone positioning in Nordic areas, the static and kinematic GNSS data in Espoo, Finland was collected with Huawei Mate 40 pro. The static and kinematic experiments were conducted in a parking lot and complex scenes in Espoo, respectively. We evaluate the quality of GNSS signals based on the satellite visibility, the carrier-to-noise density ratio, the number of tracked satellites, and the dilution of precision. In addition, we analyze the positioning performance of BDS, GPS, GLONASS, and their combinations both in static and kinematic situations. Here are the major conclusions:

1. BDS has good satellite visibility based on Huawei mate40 pro. BDS has the largest number of visible and tracked satellites in Espoo compared with other constellations. The signal carrier-to-noise density ratio of BDS-2 is comparable to GPS. However, the signal carrier-to-noise density of BDS-3 is slightly lower than BDS-2, which is due to the significant number of BDS-3 satellites at low elevation angles.

2. The horizontal precision of BDS positioning both in the static and kinematic situations is comparable to GPS in the east direction and slightly inferior to GPS in the north direction. However, the BDS shows poor precision in the up direction, which may cause by the unsatisfactory BDS-3 signals in Nordic areas in this observation period， which is too short and need to be further studied in the future.

3. The positioning of Galileo is limited by the number of visible satellites, which is less than 4 most of the time. GLONASS shows the worst positioning performance due to its discrepant ranging precision and inter-frequency code bias. The integration of BDS with other satellite systems can significantly improve the accuracy and reliability.

In conclusion, BDS has good visibility based on smartphone in Nordic areas. But the BDS-3 signals in Nordic areas in this observation period are unsatisfactory, which is partly due to the limitation of smartphone GNSS chipsets. The observation period is also too short, which can be longer in the future study. The development and modernization of smartphone hardware and the BDS system in the future will inevitably enhance the positioning performance of BDS.

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