Accuracy Evaluation of Multi-GNSS Doppler Velocity Estimation using Android Smartphones

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ABSTRACT:

The number of smartphone users has increased dramatically as smartphones have become more widely available. The mass-market urgently requires the deployment of low-cost GNSS chips in smartphones to achieve continuous, high-precision velocity and location services. Currently, most GNSS velocity determination research relies on traditional geodetic receivers and focuses on comparing velocity determination methods and analyzing velocity determination influencing factors, while research into the direction of multi-GNSS velocity determination for smartphones is insufficient. To solve this problem, we study the differences in velocity determination accuracy of Android smartphones with single-constellation, dual-constellation and multi-constellation focusing on BDS-2 and BDS-3. The results show that the accuracy of velocity determination differs significantly between different mobile phone models. The velocity determination accuracy of BDS is the highest in all single constellations, and the accuracy of BDS-2, BDS-3 and GPS are not much different. The velocity determination accuracy of dual-constellation and multi-constellation is better than single-constellation. In static velocity determination, the Huawei nova5 quad-constellation velocity determination error is in the cm/s level, while the Redmi K40 error is in the dm/s level. In kinematic velocity determination, the Huawei nova5's quad-constellation velocity determination error in horizontal and vertical directions is 1.06 dm/s and 1.77 dm/s respectively; The Redmi's quad-constellation velocity determination error in horizontal and vertical directions is 3.76 dm/s and 4.59 dm/s respectively.

1. BACKGROUNDS

The Global Navigation Satellite System (GNSS) has become an important method of acquiring location and determining velocity. It is popular with the general population for its all-around, all-weather, high-precision character(X. Wang, Wang, Ji, & Chen, 2015). The velocity of a moving vehicle can be determined economically, quickly and reliably using GNSS(He, Yang, & Sun, 2002). With the development of satellite navigation and positioning technology, ground-based receiving equipment has been gradually streamlined and using the low-cost terminal equipment to obtain high-precision navigation and positioning results is gradually becoming the main trend for the massive market location-based services(Jiahua Zhang, Tao, & Zhu, 2021).
The number of smartphone users around the world has exploded over the last decade. According to the Global Mobile Market Report 2020, the number of active smartphone users reached 3.5 billion at the end of 2020, accounting for about 45 percent of the world's population. In the next few years, the number of smartphone users worldwide will soar even further, reaching 4.1 billion by 2023. The continuous growth of the number of smartphone users has led to the smartphone's built-in low-cost GNSS chips becoming one of the main terminals used by the public to access location services.
At present, most fields, such as intelligent transportation, agriculture, disaster prevention and reduction, and public applications all need to use high-precision location information (Xu et al., 2021), so there has been some research on high-precision positioning technology. But most GNSS velocity determination research uses traditional geodetic receivers and focuses on comparing velocity determination methods, analyzing velocity determination influencing factors, analyzing velocity [1] determination models and algorithms. The research on the direction of multi-GNSS velocity determination is inadequate. Velocity is one of the most important parameters to describing the motion of an object, and high accuracy velocity information is required in precision navigation, satellite orbit determination, UAV remote sensing technology and so on. Focusing on BDS-2 and BDS-3, this paper compares the accuracy differences between Android smartphones and geodetic receivers when using single-constellation, dual-constellation and multi-constellation respectively in order to provide some data reference for a more in-depth study of multi-GNSS velocity determination for Android smartphones.

2. MULTI-CONSTELLATION DOPPLER VELOCITY DETERMINATION MODEL

In the process of positioning and velocity determination, there is always a relative movement between the satellite and the carrier, which causes the frequency of the signal received by the terminal equipment on the carrier f_r to be different from the frequency of the signal broadcast by the satellite f^s. There is a mathematical relationship between the two frequencies. In doppler shift velocity determination, the original doppler shift observation D_r^s can be obtained by subtracting between the two frequencies(Li, 2017):

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$$D_r^s = f_r - f^s = \left(1 - \frac{1}{c} * \frac{d\rho}{dt}\right) f^s - f^s = -\frac{1}{\lambda} * \frac{d\rho}{dt} \quad (1)$$

where c = velocity of light
ρ = distance between the carrier and the satellite
λ = wavelength

Combining with Equation (1), it can be seen that the complete doppler frequency shift observation equation of GNSS velocity determination using the Doppler frequency shift measurement method is as follows:

$$\lambda * D_r^s(t) = \vec{e} * (\dot{r^s} - \dot{r_r}) + c * \dot{\delta_{t_r}}(t) - c * \dot{\delta_{t^s}}(t) + \dot{I_r^s}(t) + \dot{T_r^s}(t) + \dot{\varepsilon_r^s}(t) \quad (2)$$

where $\vec{e}$ = cosine vector between station and satellite
$\dot{r^s}$ = satellite velocity
$\dot{r_r}$ = carrier velocity
$\dot{\delta_{t_r}}(t)$ = receiver clock velocity
$\dot{\delta_{t^s}}(t)$ = satellite clock velocity
$\dot{T_r^s}(t)$ = tropospheric time rates of change
$\dot{I_r^s}(t)$ = ionospheric time rates of change
$\dot{T_r^s}(t)$ = tropospheric time rates of change
$\dot{\varepsilon_r^s}(t)$ = multipath effects and noise

Since the ionosphere and troposphere change very slowly and the velocity measurement time is short, $\dot{I_r^s}(t)$ and $\dot{T_r^s}(t)$ can be ignored. So the doppler shift observation equation can be changed as follows for a single satellite:

$$\lambda * D_r^s(t) + \vec{e} * \dot{r^s} + c * \dot{\delta_{t^s}}(t) = \frac{X^s - X_r}{\rho} * \dot{X_r} + \frac{Y^s - Y_r}{\rho} * \dot{Y_r} + \frac{Z^s - Z_r}{\rho} * \dot{Z_r} + c * \dot{\delta_{t_r}}(t) \quad (3)$$

where $\dot{X_r}$ = velocity of the carrier in the X
$\dot{Y_r}$ = velocity of the carrier in the Y
$\dot{Z_r}$ = velocity of the carrier in the Z
(X^s, Y^s, Z^s) = satellite's position coordinates
(X_r, Y_r, Z_r) = carrier's position coordinates

Based on a single satellite, the doppler multi-GNSS velocity determination function model using Taylor series to linearise the observation equations is obtained as shown below:

$$\begin{bmatrix} \dot{X_r} \\ \dot{Y_r} \\ \dot{Z_r} \\ c * \dot{\delta_{t_G}}(t) \\ c * \dot{\delta_{t_R}}(t) \\ c * \dot{\delta_{t_E}}(t) \\ c * \dot{\delta_{t_C}}(t) \end{bmatrix} = (A^T P A)^{-1} A^T P \mathrm{L} \quad (4)$$

where $\dot{\delta_{t_G}}(t)$ = receiver clock rate for the GPS
$\dot{\delta_{t_R}}(t)$ = receiver clock rate for the GLONASS
$\dot{\delta_{t_E}}(t)$ = receiver clock rate for the Galileo
$\dot{\delta_{t_C}}(t)$ = receiver clock rate for the BDS
P = the weight matrix of the observation vector

we do not distinguish the difference of different satellites from the same satellite systems, but only consider the difference of observation noise and the accuracy of each satellite system in this experiment. The weights factors of 1.0, 0.5, 1.0 and 1.0 are assigned to GPS, GLONASS, Galileo and BDS system respectively.

$$A = \begin{bmatrix} \frac{X^1 - X_r}{\rho_r^1} & \frac{Y^1 - Y_r}{\rho_r^1} & \frac{Z^1 - Z_r}{\rho_r^1} & 1 & 0 & 0 \\ \frac{X^2 - X_r}{\rho_r^2} & \frac{Y^2 - Y_r}{\rho_r^2} & \frac{Z^2 - Z_r}{\rho_r^2} & 0 & 1 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{X^k - X_r}{\rho_r^k} & \frac{Y^k - Y_r}{\rho_r^k} & \frac{Z^k - Z_r}{\rho_r^k} & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

where ρ_r^n = the distance between carrier and satellite

$$L = \begin{bmatrix} \lambda * D_r^1(t) + \vec{e}_r^1 * \dot{r^1} + c * \dot{\delta_{t^1}}(t) \\ \lambda * D_r^2(t) + \vec{e}_r^2 * \dot{r^2} + c * \dot{\delta_{t^2}}(t) \\ \vdots \\ \lambda * D_r^k(t) + \vec{e}_r^k * \dot{r^k} + c * \dot{\delta_{t^k}}(t) \end{bmatrix} \quad (6)$$

According to equation (4), the velocity determination equation of a single constellation only contains four unknowns: $\dot{X_r}$, $\dot{Y_r}$, $\dot{Z_r}$ and $\dot{\delta_{t_r}}(t)$. When the number of satellites is more than four, four unknowns will be obtained. However, in the process of multi-constellation velocity determination, not only time constellation and coordinate constellation are unified, but also the deviation between systems should be considered(Geng, Ding, Xie, & Lu). We will add a clock difference variation parameter for GPS, GLONASS, Galileo and BDS respectively in the processing of parameter estimation in this paper, so there are 7 unknowns. When the number of observation satellites is more than 7, the velocity unknowns of three carriers and the clock velocity unknowns of four different systems can be solved.

3. EXPERIMENT AND RESULT ANALYSIS

Before 2016, if a smart terminal was used for GNSS navigation and positioning experiments, external components were required to implement the terminal's functions. The positioning accuracy of the terminal was also difficult to meet the requirement(Jieshi Zhang, Jiao, & Li, 2019). In May 2016, Google opened up the Application Programming Interface (API) (Guo et al., 2020) for GNSS raw observation data in the Android Nougat operating system. After that, external antennas were not necessary for positioning. Developers can directly obtain GNSS raw data and related information to calculate the raw data from GnssClock and GnssMeasurement, two native class fields that come with Android, via API. This method is only available on Android 7.0 or later(Chen, Chen, & Zhao, 2020).

In 2017, the Geo++ RINEX Logger application was released by Geo++, using the most recent Android API services to log your device's raw GNSS measurement data into a RINEX file, including pseudoranges, carrier phase, doppler frequencies and signal-to-noise ratio (Zhou, Tu, Tian, Gao, & Ge, 2021). So far, it supports GPS/GLONASS/Galileo/BDS/QZSS and has been successfully tested on many Android smart devices with Android version 7.0 or higher.

The Geo++ RINEX Logger is used for data collection in this paper. Two Android smartphones, the Huawei nova5 and Redmi K40, and a traditional geodetic receiver, the Septentrio Mosaic (for convenience of description, the three are respectively represented as Huawei, Redmi, and Septentrio) are used to collect static and kinematic experimental data on December 3, 2021 in the open field of the Sirindhorn International Research Center for Geospatial Information Science at Wuhan University.

A. Static experiment

The static experiment was conducted during the period from 16:10 to 16:40 with 30 minutes of continuous observation, a sampling frequency of 1Hz, and an elevation mask angle of 15°. The experimental equipment was placed as shown in Figure 1. After the data acquisition, the RINEX format observation files in two Android smartphones are transferred, and the ephemeris data of the desired period are downloaded from the IGS official website for velocity solving. In the static scenario, the smartphones can be considered to be doing kinematic motion with zero velocity, so zero can be directly used as the true value of velocity for accuracy evaluation.

Figure 1. Experimental equiments.

Table 1. The average number of available satellites for velocity determination in single-constellation scenarios.

Constellation	Average Number of Available Satellites		
	Huawei	Redmi	Septentrio
GPS	6.1	6.3	6.3
GLONASS	5.1	5.1	5.1
Galileo	5.7	4.9	5.9
BDS	17.0	15.9	16.0
BDS-2	10.0	10.0	10.0
BDS-3	7.0	6.0	6.0

Four satellite navigation systems: GPS, GLONASS, Galileo, and BDS can be observed by Huawei, Redmi Android smartphones and Septentrio (Shen, Guo, & Wang, 2017). Table 1 gives the average number of available satellites for GPS, GLONASS, Galileo, BDS single-constellation and BDS-2, BDS-3 velocity determination alone (for the convenience of description, they are subsequently denoted as G, R, E, C, C2, C3 respectively) for two smartphones and a receiver. The average number of available satellites for GPS is about 6; The average number of available satellites for GLONASS and Galileo is about 5. The average number of available satellites of BDS is much larger than that of GPS, GLONASS and Galileo, which is closely related to the continuous improvement and its good coverage of China's BeiDou navigation satellite system over the national territory. Since popular smart terminals tend to use GNSS linearly polarized patch antennas with higher sensitivity, the average number of available satellites for Huawei single-constellation velocity determination is slightly more than that of Septentrio overall, and the average number of available satellites for Redmi single-constellation velocity determination is basically the same as that of Septentrio. When using only the BDS-2, the average number of available satellites for both smartphone and receiver is 10. The number of available satellites for the BDS-3 is around 6, less than that of the BDS-2. BDS-2 and BDS-3 alone have a lower velocity determination accuracy than BDS-2 and BDS-3 combined.

Figures 2 and 3 give the average number of available satellites of dual-constellation and triple-constellation velocity determination respectively. The average number of available satellites for dual-constellation velocity determination is above 10, and the average number of available satellites for combined C/R and C/E velocity determination is up to 20. The average number of available satellites for triple-constellation velocity determination is above 15, and the number for combined C/R/E velocity determination is up to 25. Compared to single-constellation, the average number of available satellites is significantly higher for dual/triple-constellation. The average number of available satellites for G/C2 and G/C3 combined determination is in the range of 12-18, and the number for G/C2/C3 combined determination is in the range of 20-25. In addition, the overall average number of available satellites for Septentrio dual/triple-constellation velocity determination is between the average number of available satellites for Huawei and Redmi.

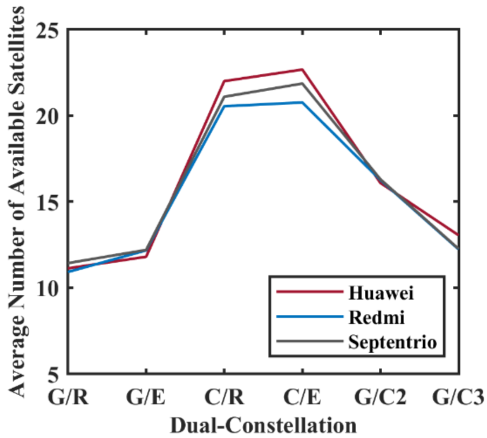

Figure 2. The average number of available satellites for velocity determination in dual-constellation.

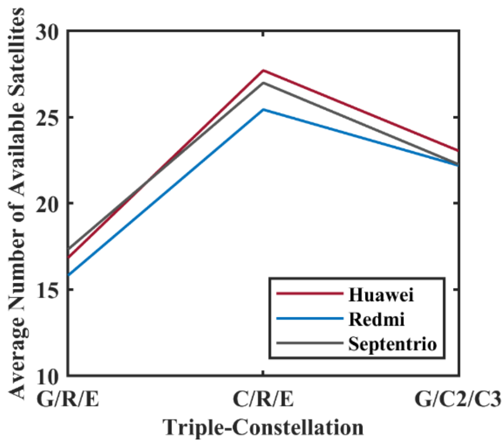

Figure 3. The average number of available satellites for velocity determination in triple-constellation.

Figure 4 gives information about the average SNR for different angles of altitude. 88% of the SNR of Septentrio is in the range of 40~50 dB; 3% of the SNR is in the range of 50~60 dB; none of the SNR is in the range of 20~30 dB. The built-in GNSS patch antennas of Huawei and Redmi Android smartphones have high sensitivity (L. Wang, Feng, & Wang, 2013), but the antenna gain is small and cannot suppress the multi-path effect, so the SNR is far inferior to that of Septentrio. 46% and 33% of the SNR for Huawei and Redmi respectively are in the range of 40-50 dB; 49% and 65% of the SNR for Huawei and Redmi respectively are in the range of 30~40 dB; there is no SNR in the range of 50~60 dB. In addition, during the entire observation period, Huawei, Redmi, and Septentrio all accounted for 58% of the available satellites in the range of 35°~75°, about 35% of the available satellites in the range of 15°~35°, and only 1% of the available satellites in the range of 75°~95°.

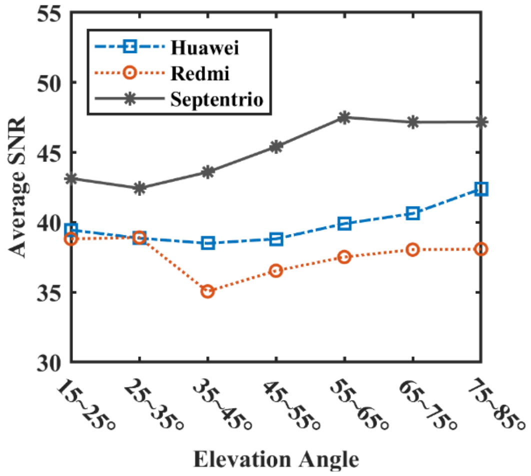

Figure 4. Average SNR for different angles of altitude.

Figure 5 and Figure 6 show the RMS histograms of the velocity determination errors in the horizontal and vertical directions of the single-constellation respectively. Except for GLONASS single-constellation, the velocity determination errors of Septentrio's other single-constellation in horizontal and vertical directions are within 1.5 cm/s and 2.5 cm/s respectively; The velocity determination errors of Huawei's other single-constellation in horizontal and vertical directions were within 1.5 dm/s and 2.0 dm/s respectively; The velocity determination errors of Redmi's other single-constellations in horizontal and vertical directions were within 4.0 dm/s and 5.0 dm/s respectively. The velocity determination accuracy of the smartphone and the receiver varies greatly and the accuracy varies greatly with the smartphone model. The velocity determination errors of GPS and BDS for Huawei respectively were 9.9 cm/s and 8.0 cm/s in the horizontal direction and respectively were 1.52 dm/s and 1.05 dm/s in the vertical direction; The velocity determination errors of BDS-2 and BDS-3 for Huawei respectively were 9.8 cm/s and 8.0 cm/s in the horizontal direction. The velocity measurement errors of BDS-2 and BDS-3 were 9.8 cm/s and 9.5 cm/s in the horizontal direction and respectively were 1.55 dm/s and 1.43 dm/s in the vertical direction. The velocity determination accuracy of BDS-2 and BDS-3 alone was the same as that of GPS. The velocity determination errors of the C2/C3 combination were 1.9 cm/s and 4.7 cm/s smaller than that of GPS in the horizontal and vertical directions respectively.

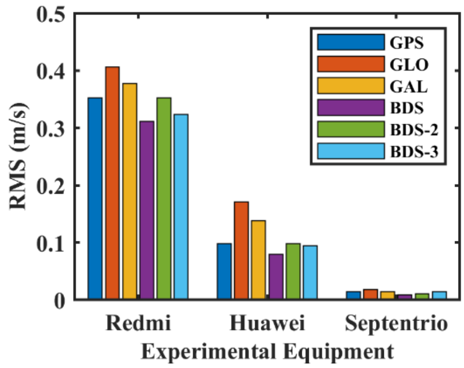

Figure 5. RMS histogram of velocity determination errors in horizontal directions of single-constellation.

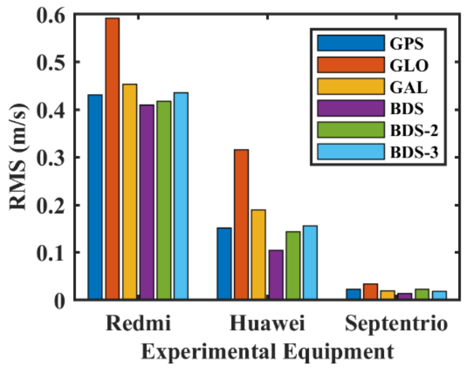

Figure 6. RMS histogram of velocity determination errors in vertical directions of single-constellation.

Table 2. RMS of triple -constellation velocity determination error. (Unit: m/s)

SYS	Huawei		Redmi		Septentrio	
	E-N	U	E-N	U	E-N	U
G/R	0.081	0.134	0.263	0.393	0.010	0.016
G/E	0.077	0.114	0.263	0.371	0.010	0.014
C/R	0.064	0.092	0.247	0.365	0.008	0.012
C/E	0.067	0.090	0.234	0.364	0.008	0.011
G/C2	0.083	0.123	0.271	0.381	0.011	0.016
G/C3	0.069	0.104	0.231	0.369	0.009	0.015
G/R/E	0.061	0.091	0.219	0.364	0.008	0.012
C/R/E	0.057	0.079	0.209	0.321	0.007	0.010
G/C2/C3	0.062	0.085	0.216	0.342	0.008	0.012

The RMS of velocity determination errors for dual/triple-constellations is given in Table 2. The velocity determination errors in the horizontal and vertical directions of Septentrio's dual-constellation are about 1.0 cm/s and 1.5 cm/s respectively. The velocity determination errors in the horizontal and vertical directions of Huawei's dual-constellation are within 1.0 dm/s and 1.0 dm/s respectively. The velocity determination errors in the horizontal and vertical directions of Redmi's dual-constellation are within 3.0 dm/s and 4.0 dm/s respectively. The accuracy of the velocity determination of triple-constellation is better than that of the dual-constellation. The velocity determination errors of Huawei's triple-constellation are around 6.0 cm/s and 8.5 cm/s in the horizontal and vertical directions respectively; The velocity determination errors of Redmi's triple-constellation are around 2.0 dm/s and 3.3 dm/s in the horizontal and vertical directions respectively. Compared with the single-constellation, the accuracy of the dual-constellation and triple-constellation has been improved.

The time series of the number of available satellites for the quad-constellation velocity determination is given in Figure 7. The RMS of the velocity determination errors in the ENU direction for the quad-constellation combination is given in Table 3. From Figure 7, it can be seen that the time series of the number of available satellites in Septentrio is more stable, while The time series of the number of available satellites in Huawei and Redmi fluctuate frequently. Combined with Table 3, it can be seen that although the number of available satellites of Huawei is larger than that of Septentrio, the accuracy of the quad-constellation velocity determination is still inferior to that of Septentrio. The errors in the horizontal and vertical directions of quad-constellation for Septentrio are 6 mm/s and 9 mm/s respectively; The errors in the horizontal and vertical directions of quad-constellation for Huawei are 4.9 cm/s and 7 cm/s respectively; The errors in the horizontal and vertical directions of quad-constellation for Redmi are 1.81 dm/s and 3.08 dm/s respectively. The number of available satellites in quad-constellation is higher than that of the single-constellation, dual-constellation and triple-constellation, and the velocity determination accuracy is the highest. The time series of residual of G26, C06 and C27 for Huawei, Redmi, and Septentrio are given in Figure 8, Figure 9, and Figure 10 respectively. The residuals of Septentrio are in the range of -1~1 m, while the residuals of Huawei and Redmi are in the range of -10~10 m.

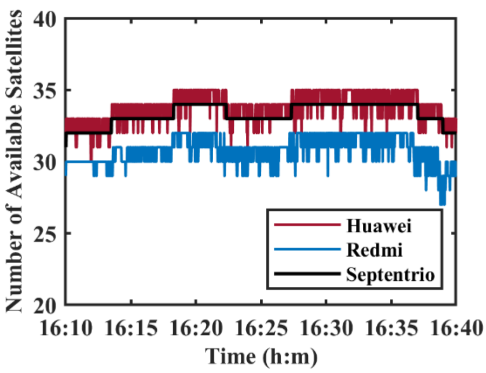

Figure 7. The time series of the number of available satellites in quad-constellation.

Table 3. RMS of the quad-constellation velocity determination error. (Unit: m/s)

Equipment	RMS			
	E	N	U	E-U
Huawei	0.032	0.036	0.070	0.049
Redmi	0.134	0.123	0.308	0.181
Septentrio	0.004	0.005	0.009	0.006

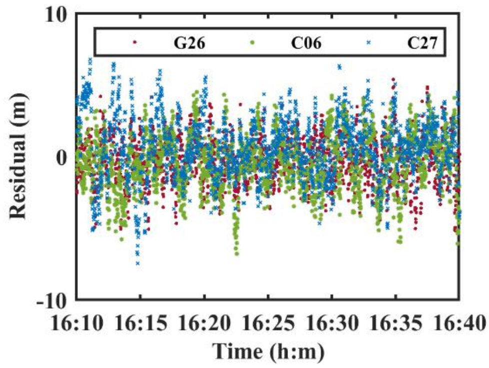

Figure 8. The time series of residual for Huawei.

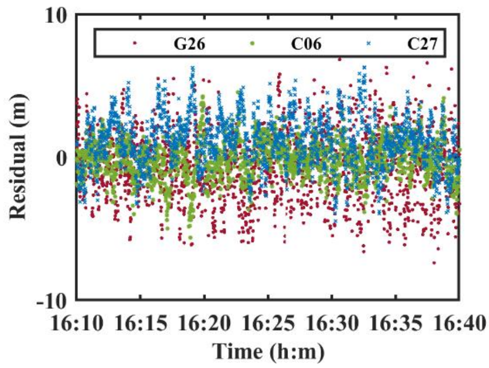

Figure 9. The time series of residual for Redmi.

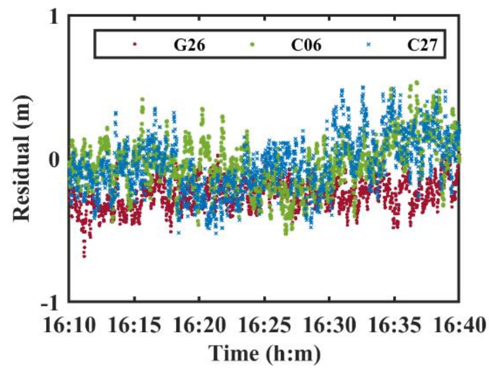

Figure 10. The time series of residual for Septentrio.

B. Kinematic experiment

The kinematic experiment was conducted using an electric vehicle, carrying two smartphones and a receiver at the same time during the time period from 17:38 to 17:58. Continuous observations were made for 20 minutes with a sampling frequency of 1Hz, and elevation mask angle of 15°. After the data acquisition, the velocity of the Septentrio was solved as the velocity reference value in the kinematic experiment to evaluate the velocity determination accuracy of the two Android smartphones. The experimental equipment placement and experimental environment are shown in Figure 11 and Figure 12 respectively.

Figure 11. Experimental equiments.

Figure 12. Experimental environment.

The average number of available satellites and average PDOP for single-constellation velocity determination is given in Figure 13 and Figure 14 respectively. The average number of available satellites for each system of Huawei and Redmi is almost equal. The average number of available satellites is about 14.5 for BDS and about 5 for BDS-3. The average PDOP of Huawei is smaller than that of Redmi, although the average number of available satellites of Huawei and Redmi are equal. The average PDOP of GPS is between BDS-2 and BDS-3. The RMS of the velocity determination errors in the ENU direction for single-constellation is given in Table 4. Except for GLONASS, the velocity determination errors of Huawei's other single-constellations are within 2.0 dm/s and 3.0 dm/s in horizontal and vertical directions respectively; The velocity determination errors of Redmi's other single-constellations are within 5.0 dm/s and 5.5 dm/s in horizontal and vertical directions respectively. The velocity determination accuracy of the smartphone showed a large difference with different smartphone models. In the kinematic velocity determination experiment, the velocity determination accuracy of BDS was better than that of GPS. The velocity determination accuracy of BDS-2 was slightly better than that of GPS. The average number of available satellites of BDS-3 was less, and the velocity determination accuracy was slightly worse than that of GPS.

Table 4. RMS of single-constellation velocity determination error. (Unit: m/s)

SYS	Huawei			Redmi		
	E	N	U	E	N	U
G	0.105	0.124	0.238	0.314	0.325	0.501
R	0.180	0.189	0.362	0.412	0.435	0.631
E	0.120	0.137	0.285	0.335	0.353	0.538
C	0.096	0.104	0.209	0.282	0.293	0.483
C2	0.102	0.119	0.237	0.312	0.329	0.496
C3	0.107	0.122	0.234	0.310	0.323	0.487

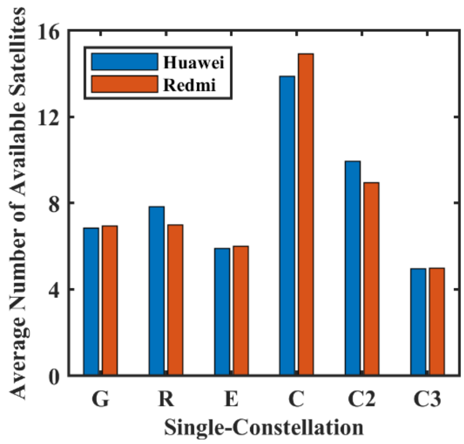

Figure 13. The average number of available satellites for single-constellation in velocity determination

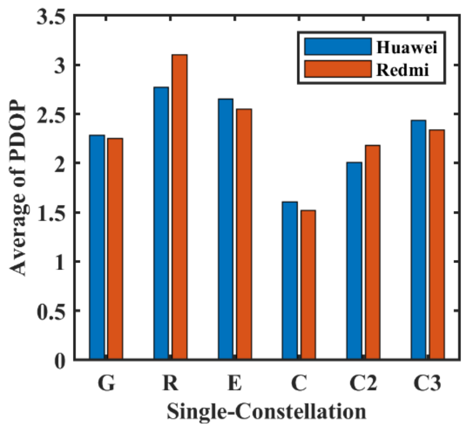

Figure 14. The average PDOP for single-constellation in velocity determination.

The average number of available satellites for Huawei and Redmi dual/triple-constellation velocity determination are given in Figure 15, and the average PDOP are given in Figure 16. The RMS of the velocity determination errors for the dual-constellation, triple-constellation, quad-constellation are given in Table 5. The average number of available satellites is above 10 for all the dual-constellation and above 20 for all the triple-constellation. Compared with the single-constellation, the average PDOP of dual-constellation and triple-constellation are significantly reduced, with the average PDOP of the dual-constellation less than 2 and the average PDOP of the triple-constellation less than 1.5. Combined with Table 5, the velocity determination errors of Huawei's dual-constellation are within 1.5 dm/s and 2.5 dm/s in the horizontal and vertical directions respectively; The velocity errors of the Redmi dual-constellation are within 4.5 dm/s in the horizontal and vertical directions, respectively. The velocity determination errors of the Redmi's dual-constellation were within 4.5 dm/s and 5.0 dm/s in horizontal and vertical directions respectively. Compared with the dual-constellation, the velocity determination errors of triple-constellation and quad-constellation for Huawei and Redmi are reduced in both horizontal and vertical directions. The velocity determination errors of quad-constellation for Huawei are about 1.06 dm/s and 1.77 dm/s in horizontal and vertical directions respectively. The velocity determination errors of quad-constellation for Redmi are about3.76 dm/s and 4.59 dm/s in horizontal and vertical directions respectively.

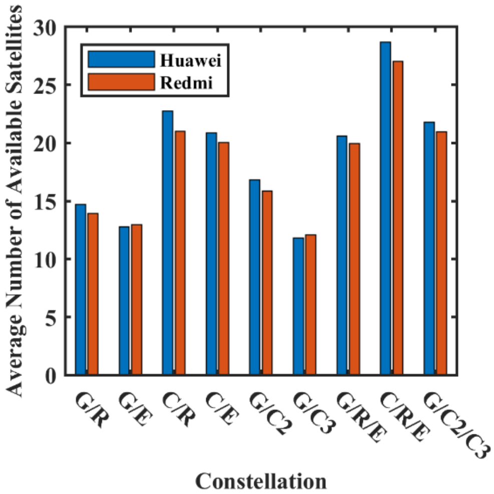

Figure 15. The average number of available satellites for dual/triple-constellation in velocity determination.

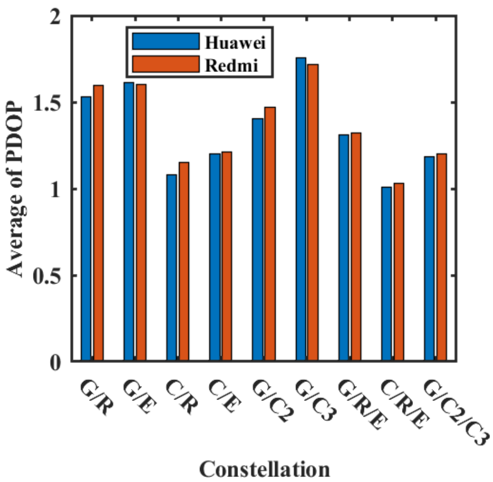

Figure 16. The average PDOP for dual/triple-constellation in velocity determination.

Table 5. RMS of dual/triple/quad-constellation velocity determination error. (Unit: m/s)

SYS	Huawei		Redmi	
	E-N	U	E-N	U
G/R	0.132	0.229	0.429	0.491
G/E	0.120	0.211	0.420	0.484
C/R	0.127	0.191	0.400	0.479
C/E	0.120	0.186	0.397	0.472
G/C2	0.126	0.233	0.412	0.481
G/C3	0.133	0.243	0.414	0.485
G/R/E	0.111	0.187	0.406	0.480
C/R/E	0.113	0.184	0.387	0.467
G/C2/C3	0.120	0.195	0.393	0.477
G/R/E/C	0.106	0.177	0.376	0.459

4. CONCLUSIONS

In this paper, we evaluate the difference in velocity determination accuracy between different Android smartphones and traditional geodetic receivers for multi-GNSS. The experimental results show that the average number of available satellites of Android smartphones is not much different from that of the geodetic receiver, but the time series of available satellites of smartphones fluctuates frequently and the PDOP is larger. The average number of available satellites of BDS velocity determination is much larger than that of GPS, GLONASS and Galileo. Among them, BDS-2 is about 10 satellites and BDS-3 is about 6 satellites. Compared with the single-constellation velocity determination, the average number of available satellites of the dual-constellation and triple-constellation increases significantly. The PDOP decreases and the velocity determination accuracy improves. The SNR of the receiver is overwhelmingly in the range of 40-50 dB, while the SNR of the smartphone is half in the range of 30-40 dB and half in the range of 40-50 dB.

In the static experiment, the velocity determination errors of Huawei single-constellation in horizontal and vertical directions are within 1.5 dm/s and 2.0 dm/s respectively; The velocity determination errors of Redmi single-constellation in horizontal and vertical directions are within 4.0 dm/s and 5.0 dm/s respectively. Compared with the single-constellation, the accuracy of the dual-constellation and triple-constellation velocity determination has improved, and the quad-constellation velocity determination has the highest accuracy. Septentrio's quad-constellation velocity determination error in both horizontal and vertical directions are within mm/s, Huawei's velocity determination error in both horizontal and vertical directions are within cm/s, and Redmi's velocity determination error in both horizontal and vertical directions are within dm/s. The velocity determination accuracy varies greatly among different models of smartphones.

The error of kinematic velocity determination is large. The velocity determination error of Huawei's single-constellation is within 2.0 dm/s and 3.0 dm/s in horizontal and vertical directions respectively; The velocity determination error of Redmi's single-constellation is within 5.0 dm/s and 5.5 dm/s in horizontal and vertical directions respectively. The velocity determination error of Huawei's dual-constellation is within 1.5 dm/s and 2.5 dm/s in horizontal and vertical directions respectively. The velocity determination error of Redmi's dual-constellation is within 4.5 dm/s and 5.0 dm/s in horizontal and vertical directions respectively. The velocity determination error of Huawei's quad-constellation is about 1.06 dm/s and 1.77 dm/s in horizontal and vertical directions respectively. The velocity determination error of Redmi's quad-constellation is about 3.76 dm/s and 4.59 dm/s in horizontal and vertical directions respectively.

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