An Improved Method Using SINS/PPP Method for Land Vehicle Gravimetry

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Abstract. Differential GNSS has been successfully applied in the SINS/GNSS vehicle gravity measurement method over the past few decades. However, GNSS error source has the spatio-temporal correlation in the differential mode. The navigation resource utilization efficiency is degraded due to the limitation of the baseline distance and the satellite common view. Using only one satellite receiver with high precision satellite orbit parameters and clock parameters, establishing navigation error models and parameter estimation methods, and obtaining high-precision receiver dynamic positioning, Precise Point Positioning (PPP) is a promising non-differential mode GNSS technique. The advantages of PPP are that it is simple to operate, low in cost, and not limited by the requirements for establishing a base station. This paper presents an SINS/PPP method for land vehicle gravimetry. Based on the strapdown gravimeter SGA-WZ02 developed by the National University of Defense Technology (NUDT), a land vehicle gravimetry test was carried out on a road about 36 kilometres long. The test consists of four measuring lines back and forth in the north-south direction with an average speed of 40 km/h. Using this method, the internal accuracy of four repeated lines is 0.52 mGal/0.9 km. Compared with the results obtained by traditional SINS/GNSS method, the internal accuracy is 0.51 mGal/0.9 km, which shows that the accuracy calculated by SINS/PPP method is comparable to the results calculated by SINS/DGNSS method. Practical gravimetry results indicate that the proposed SINS/PPP method in this paper can meet the requirements of vehicle gravimetry under ideal GNSS observation conditions, and the feasibility of PPP technology for vehicle gravimetry is verified. Finally, some discussions and suggestions about the applicability of the method and its further improvement are put forward.

1. Introduction

Kinematic gravimetry has been widely studied and applied in plenty of geophysical applications during the last few decades [1,2]. Several kinematic gravimeters of different principles such as LCR stable platform Gravimeter, the GT-series gravimeters, AIRGrav gravimeters, and the SGA-WZ series strapdown gravimeters have been developed and used for commercial geophysical surveys [3-7].

Kinematic Gravimetry can be carried out by aircraft, ships, satellites and cars. Different applications have different requirements because of different carriers. Especially in certain particular geophysics and geology applications, it requires the knowledge of a local gravity field with a level of 1-10 km spatial resolution. Therefore in the future, the land vehicle gravimetry, which has the properties of slower
velocity and closer to the earth surface, is playing and will continue to serve as an important role in many applications [8].

Differential GNSS has been successfully applied in the SINS/GNSS vehicle gravity measurement method. Under the condition of shorter baseline measurement, the differential GNSS can effectively eliminate the common error of the dual receiving stations, thus achieving the purpose of high-precision navigation and high-precision measurement [9]. However, the GNSS error source has spatio-temporal correlation. Due to the limitation of baseline distance and the requirement of satellite common-view in differential mode, the efficiency of navigation resource utilization is reduced. This limits the application prospect of differential mode GNSS in land vehicle gravimetry field to some extent. As a non-differential mode GNSS application, PPP technology has received wide attention in the past decade. Especially, with its comfortable positioning accuracy with differential GNSS, the unique characteristics of PPP technology will have many broad prospects in the future [10,11].

Based on the SGA-WZ02 developed by the National University of Defense Technology (NUDT), PPP technology was introduced to the SINS/PPP method for land vehicle gravimetry is proposed in this paper. Section 2 shows the principle of PPP and Section 3 shows the SINS/PPP method for land vehicle gravimetry. Practical experiment results of vehicle gravimetry test is shown in Section 4 with corresponding discussions. Finally, conclusions and suggestions are made in Section 5.

2. Principle of Precise Point Positioning

PPP is a satellite navigation technology that uses only one satellite receiver observation. Using high-precision satellite orbit parameters and clock parameters to establish navigation error models, PPP uses the parameter estimation method to obtain the high-precision receiver dynamic positioning information[12].

Compared with PPP, on the one hand, if the GNSS baseline distance in differential mode is too long and removing the correlation error by differential method is not ideal, the increase of the baseline length will lead to the increase of the computational residual, thus it will affect the whole-circumference ambiguity solution accuracy which in turn will affect the accuracy of positioning eventually [11]. Moreover, differential GNSS requires that the satellite signals involved in the solution must be visible to both the base station and the rover station, while this will result in a decrease in satellite utilization. If the number of satellites is insufficient, the accuracy of navigation and positioning will eventually decrease due to the unsatisfactory geometry of the satellites. Therefore, when the GNSS application conditions are not good or the differential GNSS conditions are not available, the PPP method can be considered to apply for the vehicle gravimetry task [13].

Briefly speaking, the PPP method needs to have the following conditions: First, the solution process needs to use both pseudo-range observation and carrier phase observation. Second, it requires cm-level satellite orbital positioning accuracy and ns-class satellite clock correction accuracy. Third, modeling methods are needed to estimate and eliminate the multiple GNSS error terms such as ionospheric errors, tropospheric errors, multipath effects errors, and receiver clocks, to obtain high-precision positioning solution results [14,15].

The paper will use the PPP method for vehicle gravity measurement as the background, explore the feasibility of applying PPP results to vehicle gravity measurement under PPP application modes, and then try to find an effective way to adapt the vehicle gravity measurement.

3. SINS/PPP Method for Land Vehicle Gravimetry

The principle of SINS/PPP filtering method for vehicle gravity measurement is shown in Figure 1.

(1) Collect the accelerometers and gyros data by SINS, and preform the strapdown inertial navigation solution, and then the navigation parameter values such as the specific force measurement value, the SINS position, velocity and attitude can be obtained;

(2) Calculate the PPP positioning results;

(3) Establish the SINS error model. Select position error \( \delta p \), velocity error \( \delta v \), attitude error \( \Psi \), accelerometer zero offset \( b_a \) and gyro bias \( b_g \) as state variables, and select the difference between
GNSS position, velocity and SINS position and speed as the measurement information of Kalman filter. The indirect Kalman filtering method is used to estimate the error state quantity. Use the feedback correction method to correct the navigation solution error, and then the force measurement $f^*$ in $n$–frame will be obtained after compensating for the attitude error and the accelerometer's zero offset.

![Diagram of data processing flow of SINS/PPP method](image)

Figure 1. The data processing flow of SINS/PPP method

(4) Use the results of the GNSS position and velocity obtained in Step (2), calculate the Eotvos correction and normal gravity value, and perform the second difference calculation on the GNSS position information, then the carrier acceleration $\ddot{v}^*$ can be obtained;

(5) Calculate the disturbance gravity value $\delta g^*$. Considering the low-frequency characteristics of the gravity signal, the high-frequency noise included in the gravity results needs to be filtered by low-pass filter;

(6) Implement the gravity accuracy Assessment. Assessing the gravity disturbance internal accuracy of repeated lines, and use the external reference gravity information to perform the gravity external accuracy assessment.

4. Experimental Results and Discussions

Based on the SGA-WZ02 developed by the NUDT, the land vehicle gravimetry test was carried out. The test route is shown in the green line of Figure 2.

![Image of land vehicle gravimetry test route](image)

Figure 2. Land vehicle gravimetry test route
The test route was selected in the provincial road S203 in the eastern Xinjiang province. The road is basically north-south direction. Both sides of the road are Gobi Desert, with a length of about 36 km. The average speed of the test vehicle is 40 km/h. During the whole test, the number of visible satellites is more than 6, and the GNSS observation signal is good.

In order to comprehensively and objectively evaluate the PPP positioning results, in addition to the PPP calculation of the GNSS raw data, the differential GNSS calculation is also performed in this experiment. The obtained position estimation accuracy are shown in Figure 3 and Figure 4, respectively.

![Figure 3. Position estimation accuracy of DGNSS](image1)

![Figure 4. Position estimation accuracy of PPP](image2)

From the statistical figure of position estimation accuracy, it can be seen that the east direction and north direction positioning errors of differential GNSS are less than 0.02m. The height and the total positioning error are about 0.03m. Comparing with the differential GNSS results, the east positioning error of PPP processing is about 0.02m and northward positioning error is around 0.03 to 0.04 m. The height positioning error is about 0.06 m or less. Overall, the difference of positioning results calculated by these two methods is small. Details of positioning accuracy is shown in Table 1.

| Position Accuracy | North | East | Height |
|-------------------|-------|------|--------|
| DGNSS             | 0.02  | 0.02 | 0.03   |
| PPP               | 0.03  | 0.02 | 0.06   |

PDOP value usually reflects the spatial configuration of the satellites. The PDOP values of DGNSS and PPP are shown in Figure 5 and Figure 6, respectively.

![Figure 5. The PDOP value of DGNSS](image3)

![Figure 6. The PDOP value of PPP](image4)

It can be seen that from the Figure 5 and 6, the PDOP values of the differential GNSS are mostly around 0.8 to 1.4, while the PDOP of PPP method are mainly distributed between 1.4 and 1.7. During the whole test process, whether it is differential GNSS or PPP processing method, the position estimation accuracy and PDOP value are in a stable change without frequent beating. This explains to some extent that the vehicle is running smoothly and the GNSS observation conditions of this vehicle test are acceptable [5].

In order to compare the different influence between differential GNSS and PPP processing methods on vehicle gravimetry, this experiment only uses the GNSS results calculated by different methods as variables, and the other factors such as gravimeter data, filtering parameters, and accuracy statistical
methods all adopt the same configuration. Firstly, using the differential GNSS processing result to the SINS/GNSS method, the statistical results of the gravity accuracy are obtained. Then, only replacing the DGNSS data with the PPP results, the gravity measurement results of SINS/PPP method with PPP results can be obtained. Results of SINS/PPP method are shown in Figure 7.

![Figure 7. Internal accuracy results of SINS/PPP method](image)

Statistics of the internal accuracy by SINS/GNSS and SINS/PPP method are shown in Table 2.

|                | Max   | Min   | Mean | RMS  | Total RMS |
|----------------|-------|-------|------|------|-----------|
| **SINS/DGNSS** |       |       |      |      |           |
| Line 1         | 0.98  | -2.30 | 0.00 | 0.39 | 0.52      |
| Line 2         | 1.13  | -1.54 | 0.00 | 0.51 |           |
| Line 3         | 2.32  | -1.09 | 0.00 | 0.70 |           |
| Line 4         | 1.07  | -0.98 | 0.00 | 0.47 |           |
| **SINS/PPP**   |       |       |      |      |           |
| Line 1         | 1.01  | -2.65 | 0.00 | 0.42 | 0.51      |
| Line 2         | 1.27  | -1.39 | 0.00 | 0.47 |           |
| Line 3         | 2.73  | -1.01 | 0.00 | 0.69 |           |
| Line 4         | 1.17  | -0.88 | 0.00 | 0.41 |           |

As can be seen from Table 2, the internal accuracy calculated by SINS/PPP method is 0.51mGal/0.9km, while the accuracy obtained by SINS/DGNSS is 0.52mGal/0.9km. There is almost no difference between these two methods. It can be seen from this test that both differential GNSS and PPP can be used for vehicle gravity measurement under the condition of ideal GNSS observation conditions, and the measurement accuracy of the gravity disturbance is nearly equivalent. This shows that in the case of ideal observation environment, the SINS/PPP method can be applied for implementing the land vehicle gravimetry test by using only one rover station. Adopting PPP technology can save cost and improve efficiency without losing the accuracy of data measurement.

5. Conclusion

GNSS error source has the spatio-temporal correlation in the differential mode. The navigation resource utilization efficiency is degraded due to the limitation of the baseline distance and the satellite common view. Precise Point Positioning (PPP) is a promising non-differential mode GNSS technique. The advantages of PPP are simple to operate, low in cost, and not be limited by the requirements for establishing a base station. This paper presents an SINS/PPP method for land vehicle gravimetry. Based on the strapdown gravimeter SGA-WZ02 developed by the National University of Defense Technology (NUDT), a land vehicle gravimetry test was carried out on a road about 36 kilometers long with an average speed of 40km/h. The test consists of four repeated lines in the north-south direction. The internal accuracy of four repeated lines is 0.52mGal/0.9km by SINS/PPP method presented in this paper. Compared with the results obtained by traditional SINS/GNSS method, the internal accuracy is 0.51mGal/0.9km, which shows that the accuracy calculated by SINS/PPP method is comparable to the
results calculated by SINS/DGNSS method. Practical gravimetry results indicate that the proposed SINS/PPP method can meet the requirements of vehicle gravimetry under ideal GNSS observation conditions, and the feasibility of PPP technology for vehicle gravimetry is verified.

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References

[1] Zhang K 2007 Research on the Methods of Airborne Gravimetry Based on SINS/DGPS NUDT Changsha China.
[2] Yu R, Wu M, Cao J, Zhang K and Cai S 2018 A new method of GNSS fault data detection for strapdown land vehicle gravimetry IEEE International Conference on Applied System Invention (ICASI) Chiba Japan pp 299-302.
[3] Zhang K, Wu M and Cao J 2010 The Status of Strapdown Airborne Gravimeter SGA-WZ 2010 International Symposium on Inertial Technology and Navigation Nanjing China
[4] Bruton A, Hammada Y and Ferguson S 2010 A Comparison of Inertial Platform, Damped 2-Axis Platform and Strapdown Airborne Gravimetry International Symposium on Kinematic System in Geodesy, Geomatics and Navigation, KIS2001 Banff Canada: 542-550.
[5] Studinger M, Bell R and Frearson N 2008 Comparison of AIRGrav and GT-1A airborne gravimeters for research applications. Geophysics 73 I51–I61.
[6] Olson D 2010 GT-1A and GT-2A Airborne Gravimeters: Improvements in Design, Operation, and Processing from 2003 to 2010 Airborne Gravity 2010.
[7] Cai S, Wu M, Zhang K and Cao J 2013 The First Airborne Scalar Gravimetry System Based on SINS/DGPS in China. Sci. Chin. Earth Sci. 56 2198–2208.
[8] Yu R, Cai S, Wu M, Cao J and Zhang K 2015 An SINS/GNSS Ground Vehicle Gravimetry Test Based on SGA-WZ02 Sensors 15 23477–23495.
[9] Yu R 2017 Research on Key Technologies for Strapdown Ground Vehicle Gravimetry NUDT Changsha China.
[10] Titterton D and Weston J 2004 Strapdown Inertial Navigation Technology 2nd ed American Institute of Aeronautics and Astronautics USA.
[11] Yu R, Wu M, Zhang K, Cai S, Cao J, Wang M and Wang L 2017 A New Method for Land Vehicle Gravimetry Using SINS/VEL Sensors 17 766.
[12] Li X 2013 High Accuracy Kinematic Acceleration Determination for Airborne Gravity Surveying NUDT Changsha China.
[13] Li X, Wu M, Zhang K, He X and Huang Y 2013 An improved approach to network ambiguity validation by applying outlier detection to the baseline measurement errors. Surveys in Geophysics 34(2) 165-180.
[14] Wang J, Satirapod C and Rizos C 2002 Stochastic Assessment of GPS Carrier Phase Measurements for Precise Static Relative Positioning Journal of Geodesy 76 (2) 95-104.
[15] Kennedy S 2002 Acceration Estimation from GPS Carrier Phase for Airborne Gravimetry University of Calgary Canada.