Survey Review

ISSN: 0039-6265 (Print) 1752-2706 (Online) Journal homepage: http://www.tandfonline.com/loi/ysre20

A novel Stop&Go GPS precise point positioning (PPP) method and its application in geophysical exploration and prospecting

X H Zhang, F Guo & X X Li

A novel Stop&Go GPS precise point positioning (PPP) method and its application in geophysical exploration and prospecting

X. H. Zhang*, F. Guo and X. X. Li

A new method of Stop&Go positioning method based on PPP is proposed in this paper with an application to geophysical exploration and prospecting. The method couples the kinematic PPP and static PPP, where the continuous kinematic observations between two sequential short static observations provide a correction for the carrier phase ambiguities. Therefore, the whole consecutive observations, including both static and kinematic segments, will contribute to the ambiguities convergence of each point with few epochs' static observation. The experimental results showed that for the measured points which are observed over 60 s with 5 s sampling rate in static mode, the positioning accuracy can reach 5–6 cm in the horizontal and 0·1 m in the vertical; for those points which are observed over 10 s with 5 s sampling rate in static mode, the positioning accuracy is about 8–9 cm in horizontal and 0·12 m in vertical.

Keywords: Stop&go precise point positioning, GPS, Geophysical exploration, Geophysical prospecting

Introduction

Surveying and mapping play an important role in geophysical prospecting and exploration. They are used for staking out pre-designed points in the field, drawing sketch maps, and supplying reliable geolocation information [**4**]. Traditionally, a theodolite with measuring tacheometry was adopted for geophysical prospecting surveying. Recently, advanced technologies, such as GPS and total station, are widely applied to replace the theodolite for above applications [**10**]. Nowadays, Real Time Kinematic (RTK) and post-processing kinematic (PPK) techniques have become the major method for geophysical prospecting and exploration surveying. Since geophysical prospecting surveying operations often take place in remote mountainous areas with hostile environment, the RTK data link between the rover and base receiver station is usually not accessible. In such cases, RTK technology is not applicable, and only the PPK is feasible in the field.

PPK originated from a fast static positioning method known as 'Stop&Go', which was first proposed by Remondi in 1986 [**7**], and cm-level accuracy can be obtained with a couple of seconds GPS carrier phase measurements if their integer ambiguities can be resolved correctly. As a fast relative static positioning method, the traditional 'Stop&Go' techniques requires at least one reference station, and the distance between the rover point and the reference station must be within a certain range, usually less than 20 km. As a result the users have to deploy multiple reference stations for a large scale surveying area, which would increase logistical complexity and reduce the operational efficiency.

In recent years, the precise point positioning (PPP) technique has gained wide attention since it does not require a local reference station. It presents a definite advantage for many applications in terms of operational flexibility and cost-effectiveness compared to the double difference RTK techniques. However, a fairly long initialisation time, which ranges from 1–2 h to obtain cm-level accuracy, has limited its application to real-time applications with current PPP method based on pure static or pure kinematic positioning modes as phase ambiguities converge to constant values and the solution reaches its optimal precision, taking full advantage of the precise but ambiguous carrier phase observation [**3**], [**2**], [**5**], [**8**]. The proposed PPP based Stop&Go method in this paper demonstrates that it can provide high positioning accuracy with only a short period of observations such as a few seconds. The method will be useful for some applications where RTK or DGPS is not feasible.

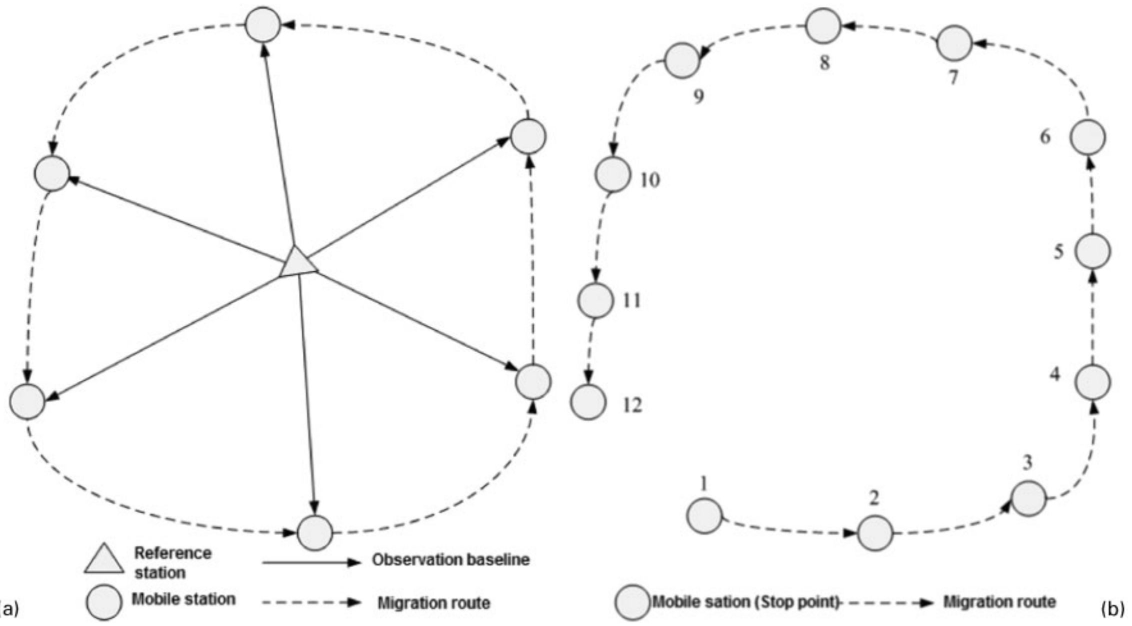
A Stop&Go positioning method based on PPP technique

The traditional fast positioning methods, such as RTK and PPK, are relative positioning techniques which require local reference stations as shown in Fig. 1*a*. For RTK and PPK, the initialisation operation at the rover receiver requires static occupation for a short period of time to resolve the integer ambiguity values of the double difference carrier phase observations. Continuous

School of Geodesy and Geomatics, Wuhan University, 129 Luoyu Road, Wuhan 430079, China

*Corresponding author, email xhzhang@sgg.whu.edu.cn

Received 30 November 2011; accepted 30 November 2011
DOI 10.1179/1752270611Y.0000000016



a traditional Stop&Go based on relative positioning; *b* proposed absolute Stop&Go positioning
1 Relative and absolute Stop&Go positioning

tracking of GPS satellites must be kept when the rover receiver travels from one point to another. To ensure the positioning accuracy, the baseline length between the reference and rover receivers stations should be typically no more than 15 km [**6**].

The Stop&Go PPP method proposed herein is an absolute positioning method which is based on PPP to combines both kinematic and static positioning as shown in Fig. 1*b*. The users hold a single GPS receiver on the measured point (Stop point) for several epochs, keep continuous tracking of the visible satellites, then move the receiver to the next Stop point and perform static observation for desired number of epochs, repeat the above procedures for remaining points. To guarantee the positioning accuracy and reliability of the Stop points, the recommended time period of a continuous operation session should not be less than 1h. The new Stop&Go PPP method offers more flexibility in the field operation and it also eliminates the requirement for local reference stations. As a result, it can significantly reduce the costs and increase productivity.

The Stop&Go PPP model

The Stop&Go PPP positioning is an absolute positioning method, and its core algorithm is PPP. Unlike static or kinematic PPP positioning, the Stop&Go PPP model is based on a PPP model in which the kinematic positioning and static positioning are carried out in an alternate manner. The observation equation and the error correction model in the Stop&Go PPP model are the same with those of the standard PPP [**9**], but its parameter estimation strategy is different from the standard PPP.

Observation equation

For standard static and kinematic PPP models, the ionosphere-free combinations with dual-frequency are widely applied

$$l_P = \rho + d_{\mathrm{orb}} + c\cdot(\mathrm{d}t - \mathrm{d}T) + M\cdot zpd + \varepsilon_{\mathrm{P}} \quad (1)$$

$$l_\Phi = \rho + d_{\mathrm{orb}} + c\cdot(\mathrm{d}t - \mathrm{d}T) + amb + M\cdot zpd + \varepsilon_\Phi \quad (2)$$

where, l_{P} is the ionosphere-free pseudo-range combination of P1 and P2, l_Φ is the ionosphere-free phase combination (in the form of distance) of L1 and L2, d_{orb} is the deviation of satellite orbit, $\mathrm{d}t$ and $\mathrm{d}T$ are the clock biases of ground GPS receiver and GPS satellite respectively, c is the velocity of light in vacuum, λ is the wave length of combined phase observation, amb is the ambiguity (real number) of ionosphere-free phase combination, zpd is the zenith tropospheric delay parameter, M is the mapping function of the troposphere, ε_{p}, ε_Φ are the remaining noise of pseudo-range and phase combination, and multi-path effect as well, and ρ is the geometric distance between the receiver antenna phase centre (x, y, z) and GPS satellite antenna centre (X_{s}, Y_{s}, Z_{s}).

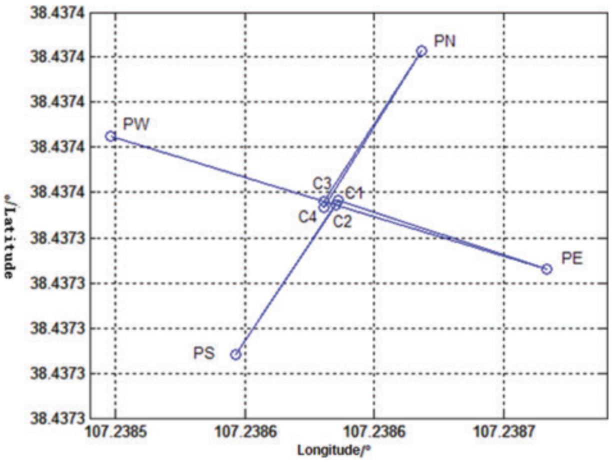
Error correction strategy

The error corrections can be made similarly as the standard PPP. Most of the errors can be reduced using techniques such as:

(i) satellite orbit error and satellite clock error can be greatly reduced using post-processing precise ephemeris and clock products published by IGS (International GNSS Service)
(ii) ionospheric delay can be eliminated by combining the dual-frequency observations
(iii) dry component of the tropospheric delay, antenna phase-centre bias, phase wind-up, relativistic effect, earth rotation and tide effect can be precisely corrected by using existing correction models
(iv) the wet component of the tropospheric delay that cannot be precisely modelled are estimated with additional parameters
(v) receiver clock biases should also be estimated epoch by epoch.

Parameter estimation

After taking comprehensive and precise error corrections procedures as mentioned above account, the



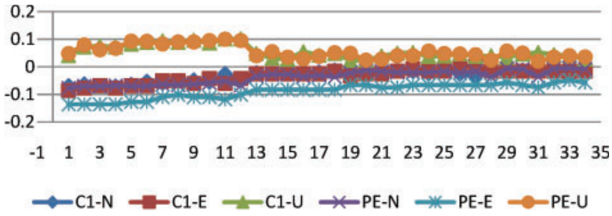
2 Layout of Stop points

linearisation of the observation equation can be written as follow

$$\mathbf{V}=\mathbf{A}\cdot\mathbf{X}+\mathbf{W},\ \mathbf{P} \tag{3}$$

where, **V** is the residual vector, **A** is the design matrix, **W** is misclosure vector, **P** is weight matrix, and **X** is the parameter vector to be estimated, $\mathbf{X}=[x(k)\ y(k)\ z(k)\ \mathrm{d}t(k)\ zwd\ amb^j]^{\mathrm{T}}$. In the vector, $x(k)$, $y(k)$, $z(k)$ are the 3D coordinates of the receiver at a location, k is the number of locations. On a Stop point $k=1$, which means no position change happens during the observed epochs on any Stop point. For the kinematic stage between two Stop points, k value equals the number of epochs during the kinematic stage, $\mathrm{d}t(k)$ is the receiver clock error at epoch k, zwd is the wet component of zenith delay, amb is the ambiguity of phase combination, j refers to the number of satellites. Details about the PPP stochastic models can be found in [**3**].

Compared with the traditional static or kinematic PPP models, the Stop&Go PPP model combines the alternating static and kinematic PPP. The observations in both static and kinematic stage can be fully used to estimate the position coordinates, receiver clock error and the ambiguity parameters. Whenever a cycle slip occurs or a new satellite is observed, the related ambiguity parameters need to be re-estimated or adjusted. zwd can be estimated using piecewise constant (e.g. estimate one parameter per 2 h) or piecewise linear. For positioning in the kinematic mode, the three-dimension coordinates are calculated epoch by epoch but only one position will be estimated at Stop points using accumulative epochs of static observations at that point. The ambiguity parameters can be connected by the continuous observations during the entire continuous surveying session. The essence of this method is to use accumulated observations from point to point to enhance the solution reliability of the ambiguities estimation. The reliable fixing of the estimated ambiguities by this way could decrease the necessary occupation time of a receiver at a Stop point. In this way, the continuous kinematic observations between two different surveying points provide connection of the ambiguities. Therefore, the whole consecutive session including both static and kinematic segments will contribute to the ambiguities convergence at the Stop point with only a few epochs' static observation.



3 Positioning error of Stop&Go PPP for points *C1* and *PE*

A Least Square or Kalman Filtering estimation approach can be used for parameters estimation in PPP. The Recursive Least Square Method has been used that classifies the parameters to be estimated and processes them recursively to resolve the difficulty of high-order normal equation matrix inversion. The method can save computing resources and improve computing efficiency. In this way, the data processing efficiency can be greatly enhanced [**1**].

Results and analyses of Stop&Go PPP

Experiment description

Four Trimble 5700 GPS dual-frequency receivers were used to conduct the Stop&Go experiments at eight points, namely *PE, PS, PW, PN, C1, C2, C3* and *C4* (locations are shown in Fig. 2) in a petroleum prospecting surveying site in the north of China. The size of test area is about 10×20 m. The data sampling interval of the GPS receiver was set to 5 s, the continuous observation duration is about one and half hours. The four receivers performed position determination along four routes (*C1-PE, C2-PS, C3-PW* and *C4-PN*) simultaneously and the operators went back and forth on each route 30 times, and performed static observation at each point for 1 min.

Software developed by the authors based on the Stop&Go PPP model was used to process the above experiment data, from which the three-dimension coordinates of all the Stop points can be calculated. To verify the obtainable positioning accuracy of the proposed method, a reference station was installed in the test area at the same time, and the coordinates of the reference station are known with accuracy of better than 1 cm which was determined beforehand with a long static observation. The Trimble Geomatics Office (TGO) software was used to solve the baselines between the Stop points and reference station, so all the Stop points coordinates can be determined with cm accuracy and are used as the reference to evaluate the positioning accuracy of the Stop&Go PPP method.

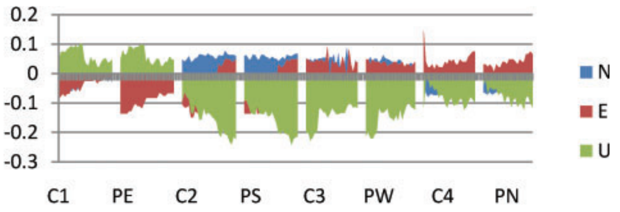
Results and analyses

Results of 60 s static observation on a Stop point

The difference of each coordinate component between position solutions from the Stop&Go PPP and the reference value for route *C1-PE* are provided in Fig. 3. The vertical axis represents the positioning error (in m), and the horizontal axis stands for the observation array of point *C1* or point *PE*.

The statistic mean bias (mean), standard deviation (STD) and root mean square (RMS) of the above solutions are summarised in Table 1.

Based on Table 1, the horizontal accuracy for both points is about 0·05 m while the vertical precision is



4 Positioning error of Stop&Go PPP for all Stop points

approximately 0·06 m for both points C1 and PE. Similar results are obtained for other three Stop&Go routes. The results for all points from different Stop&Go routes (*C1-PE, C2-PS, C3-PW* and *C4-PN*) are shown in Fig. 4, where the horizontal axis refers to the time array of each Stop point and the vertical axis is the positioning error (in m) of Stop&Go PPP in NEU components.

Figure 4 indicates that the systematic deviations are the same for the positioning results of the two Stop points on the same route, which may be attributed to systematic errors between models used by PPP and PPK since PPP solution is based on processing of non-differenced observations while PPK solution is based on double differenced observations. By making the difference of the two Stop points on the same route, the baseline vectors with higher accuracy could be obtained after the bias was reduced. Almost all the positioning results for the north–south component have relatively better accuracy of around 5 cm; the east–west component accuracy is worse with a maximum deviation of 0·15 m (*C4* point); the vertical component has the worst accuracy with a maximum deviation of 0·20–0·25 m.

The statistic results listed in Table 2 indicate that the Stop&Go PPP method can achieve a 5–6 cm accuracy in horizontal and 0·1 m in the vertical with a sampling interval of 5 s and a 60 s static observation time at a Stop point.

Results of 10 s static observation on a Stop point

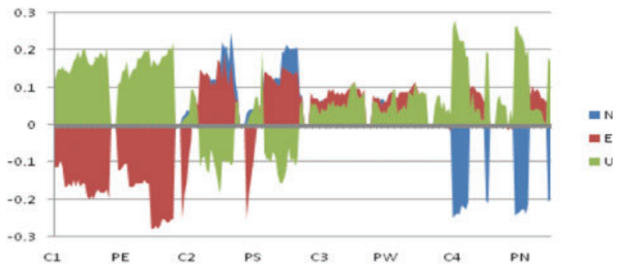
To further analyse the effect of the observation duration (number of the observation epochs) at the Stop points on the PPP positioning accuracy, a second Stop&Go

Table 1 Statistics of Stop&Go PPP solution for points C1 and PE

Stop points	Statistics values	Components/m N	E	U
C1	Mean	−0·030	−0·033	0·055
	STD	0·021	0·024	0·024
	RMS	0·037	0·041	0·060
PE	Mean	−0·037	−0·088	0·055
	STD	0·023	0·027	0·024
	RMS	0·044	0·092	0·061

Table 2 Statistics error of Stop&Go PPP for all Stop points

Statistic values	Components/m N	E	U
Mean	−0·005	−0·008	−0·071
STD	0·045	0·060	0·097
RMS	0·046	0·061	0·119



5 Positioning error of Stop&Go PPP for all Stop points

PPP positioning experiment was carried out at the above eight Stop points, with the same sampling rate, but the occupation time of static observations at the Stop points decreased to 10 s, which meant that there were only two epochs observed at each Stop point. A similar processing and comparison strategy was used as in the first experiment. The positions of all the Stop points are determined using the TGO (PPK) software and the Stop&Go PPP software, respectively. The positioning errors of each Stop&Go route (*C1-PE, C2-PS, C3-PW* and *C4-PN*) are shown in Fig. 5 and their statistics results are given in Table 3.

Comparing Fig. 5 with Fig. 4, and Table 3 with Table 2, there is a similar systematic deviation for the solutions between the two Stop points on the same route. On the other hand, a decrease in observation time at a Stop point will degrade the positioning accuracy. In such a case the maximum positioning error may reach a few decimetres.

Conclusions and recommendations

A novel positioning techniques has been proposed by extending the traditional PPK method to a new PPK method based on PPP. The method has been applied to geophysical prospecting surveying for the first time and achieved the desired performance. This positioning method can provide 1 cm to 0·1 m accuracy for fast static positioning applications. Though the PPK processing method can also produce similar positioning accuracy, the new PPP based Stop&Go approach enables more flexible operation in the field work and less costs as no local reference stations are necessary. This method can reduce the occupation time to one minute at a surveying point compared to the standard PPP which generally takes more than half an hour to achieve cm-level accuracy. It can become a useful alternative for users working in remote mountainous areas where RTK or DGPS becomes difficult. However, it should be noted that the proposed method cannot shorten the convergence time of PPP solution, i.e. the length of the whole period of continuous operation should be longer than half an hour while static periods at Stop point could be one minute more or less.

Table 3 Statistics error of Stop&Go PPP for all Stop points

Statistic values	Component/m N	E	U
Mean	0·019	0·038	0·059
STD	0·078	0·085	0·109
RMS	0·080	0·093	0·124

Acknowledgements

This study was supported by the Foundation for Innovative Research Group of the National Natural Science Foundation of China (Grant No. 41021061) and National Natural Science Foundation of China (No. 40874017 and 41074024). The authors would like to thank the IGS community for the data used in this paper.

References

1. Chen, W., Hu, C., Li, Z., Chen, Y., Ding, X., Gao, S. and Ji, S., 2004. Kinematic GPS Precise Point Positioning for Sea Level Monitoring with GPS Buoy. *Journal of Global Positioning Systems*, 3(1): 302–307.
2. Gao, Y. and Shen, X. 2001. Improving Ambiguity Convergence in Carrier Phase-Based Precise Point Positioning. *Proceedings of ION GPS Meeting*, Institute of Navigation, Salt Lake City, UT: 1532–1539.
3. Kouba, J. and Heroux, P. 2001. Precise Point Positioning Using IGS Orbit and Clock Products. *GPS Solutions*, 5(2): 12–28.
4. Liu, D., Ding, X. and Yang, B. 2007. Discussion about GPS RTK in Geophysical Exploration. *Coal Technology*, 26(10): 130–132.
5. Liu, J. and Shirong, Y. E. 2002. GPS Precise Point Positioning Using Undifferenced Phase Observation. *Geomatics and Information Science of Wuhan University*, 27(3): 234–239.
6. Ogaja, C., Rizos, C., Wang, J. and Brownjohn, J. 2001. Toward the Implementation of on-line Structural Monitoring Using RTK GPS and Analysis of Results Using the Wavelet Transform. *Proceedings of 10th FIG International Symposium on Deformation Measurement*, 9–22 March, Orange, CA: 284–293.
7. Remondi, B. W. 1986. Performing Centimeter-Level Surveys in Seconds with GPS Carrier Phase: Initial Results. *Journal of the Institute of Navigation*, 32(4): 386–400.
8. Zhang, X. and Andersen, O. B., 2006. Surface Ice Flow Velocity and Tide Retrieval of the Amery Ice Shelf Using Precise Point Positioning. *Journal of Geodesy*, 80(4): 171–176.
9. Zhang, X., Liu, J. and Forsberg, R., 2006. Application of Precise Point Positioning in Airborne Survey. *Geomatics and Information Science of Wuhan University*, 31(1): 19–22.
10. Zhang, Y., 2006. Application of GPS-RTK Technology in Geophysical Prospecting Surveying in the City Zone, Shandong University of Science and Technology.