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Cross-ocean GPS long distance rapid static positioning methods

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Abstract: The method of cross-ocean GPS long distance rapid static positioning has become one of the main technical means of GPS static positioning away from the mainland. The key technology had been analyzed including data preprocessing and quality control, long distance integer ambiguity resolution and static Kalman filter parameter estimation. Effective data processing method of cross-ocean GPS long baseline rapid static positioning had been proposed. Through the analysis of practical examples of coastal and ocean, the feasibility of cross-ocean GPS long distance rapid static positioning based on the method is testified and verified. The results show that the accuracy of one-hour single baseline static positioning for the 500 – 600 km distance can be better than 10cm in the three-dimensional coordinates, which can suffice static positioning accuracy in the special ocean environment.

Key words: cross-ocean; rapid static positioning; data preprocessing; integer ambiguity; static Kalman filter

1 Introduction

With ongoing development of GPS positioning theory and data processing technology, GPS has reached 10^{-9} accuracy level currently in static relative positioning, which is widely used in terrestrial reference frame maintenance, crustal deformation monitoring, geodynamic research and all grades of GPS control network layout. Ionosphere and troposphere errors correlation decreases with increasing the baseline distance, so in general extending the observation time is put in practice in order to get accurate baseline vector, but the traditional method of static relative positioning is difficult to meet the positioning requirements of the offshore locations. GPS reference stations are generally set up in the coastal areas of the mainland, whereas GPS island stations are far from continent. For the island location-based application in GPS campaign of the continental base stations and island stations, island shoreline surveys on the spot and island of surveying and mapping, the factor of marine special observation environment causes the problems of poor quality and short observation time of GPS data and the long distance baseline, so cross-ocean GPS long distance rapid static precise positioning is facing new challenges. The research on data processing of cross-ocean long distance rapid static positioning has not only an important theoretical significance, but also an important practical application. Few studies about cross-ocean GPS long distance (more than 500 km) rapid precise positioning had been done in the world. Colombo et al[1,2] investigated on cross-sea long baseline kinematic positioning and the floated ambiguities rapid convergence to achieve sub-decimeter accuracy. Carrier phase ambiguity resolution is one of the key technologies for GPS applied to long baselines. At present, the widely used method is to resolve wide lane ambiguity with the code and carrier phase, and then introduce wide lane integer ambiguity into the ionosphere free solution to further determine the narrow lane ambi-

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guity[3-8]. In this paper, on the basis of the principle of GPS static relative positioning, data processing effective method of cross-sea long baseline fast static positioning is proposed, the positioning accuracy of the different baseline length is analyzed and compared by experimental data. The results show that the accuracy of one-hour single baseline static positioning for the distance 500 – 600 km can be better than 10 cm in the three-dimensional coordinates, which can suffice static positioning accuracy in the special ocean environment.

2 Models and methods

2.1 GPS observation model

The traditional relative positioning mode is introduced in the cross-ocean GPS long distance rapid static positioning, that ionosphere-free combination of double difference observation values constitutes the observation model, which is simplified as follows[9]:

$$V_{\Phi}(i) = \nabla\rho(i) + \nabla\lambda\ \nabla N(i) - \nabla\lambda\ \nabla\Phi(i) + \nabla\rho_{\mathrm{trop}}(i) + \varepsilon_{\Phi} \tag{1}$$

where i is the observation epoch, $\nabla\Phi(i)$ is the combined double difference observation to eliminate the ionosphere impact, $V_{\Phi}(i)$ denotes the observation error, $\nabla\lambda$ and $\nabla N(i)$ represent the corresponding wavelength and ambiguity respectively, $\nabla\rho(i)$ is the double difference distance from a satellite to a receiver, $\nabla\rho_{\mathrm{trop}}(i)$ is the double difference troposphere delay impact, ε_{Φ} is the observation noise and with no modeled error.

2.2 Data preprocessing method

Data preprocessing is key to GPS baseline solution, including cycle slip detection and repair, and observation gross error rejection, with the purpose to obtain high quality double difference observation in order to establish observation equation. In this paper, three difference observation is adopted to cycle slip detection and quality analysis, and it is composed of double difference observations:

$$\delta L = \nabla L_{i+1} - \nabla L_i \tag{2}$$

where ∇L_i and ∇L_{i+1} represent the double difference observation between the adjacent epochs. Three difference observations which is the difference of double difference observations eliminates the effects of satellite clock error, receiver clock error and double difference integer ambiguity, and meanwhile weakens the effects of satellite ephemeris and atmospheric propagation delay error. The observation equation only contains the unknown baseline vectors, atmospheric error change and measurement noise, so by the size of the cycle slip δL, gross error and observation noise can be distinguished between the adjacent epochs. At the same time, the size of the observation noise can provide the basis observation weight for positioning solution.

2.3 Long-distance double difference integer ambiguity

2.3.1 Double difference wide-lane ambiguity

The initial double difference wide-lane ambiguity is first estimated by the Melbourne-Wübbena double difference combination observation, and then double difference wide-lane ambiguity is finally determined through taking the average of those double difference wide-lane ambiguities in multiple epochs. Melbourne-Wübbena double difference combination observation is expressed[3,4]:

$$\nabla L_6 = (f_1\ \nabla L_1 - f_2\ \nabla L_2)/(f_1 - f_2) - (f_1\ \nabla P_1 + f_2\ \nabla P_2)/(f_1 + f_2) \tag{3}$$

$$\nabla N_{\mathrm{WL}} = \nabla L_6 (f_1 - f_2)/c \tag{4}$$

where f_1 and f_2 respectively represent the frequency of the carrier L_1 and L_2, ∇L_1 and ∇L_2 respectively represent the double difference observation of carrier L_1 and L_2, ∇P_1 and ∇P_2 respectively represent the double difference observation of pseudo range P_1 and P_2, ∇N_{WL} is the double difference wide-lane ambiguity, and c is the speed of light in vacuum.

In equation (4), the Melbourne-Wübbena double difference combined observation has nothing to do with the location of the satellite orbit and station, while the impacts of troposphere delay error, satellite clock error, receiver clock error and ionosphere delay error are removed on carrier phase and pseudo range. Therefore, the double difference wide-lane ambiguity resolution is affected only by noise; double difference wide-lane ambiguity can be resolved through taking the average of those double difference wide-lane ambiguities in multiple epochs.

2.3.2 L_1 and L_2 double difference ambiguity

When double difference wide-lane ambiguity is determined, double difference ambiguity of ionosphere-free combination can be expressed into the combination between the double difference wide-lane ambiguity and double difference ambiguity of carrier L_1 [10]:

$$\nabla N_{LC} = 77\ \nabla N_1 - 60\ \nabla N_2 = 17\ \nabla N_1 + 60\ \nabla N_{WL} \quad (5)$$

where ∇N_{LC} is the double difference ambiguity of the combination of the ionosphere, ∇N_1 and ∇N_2 represent the double difference observation of carrier L_1 and L_2 respectively, double difference ambiguity of the carrier for the double difference wide lane ambiguity, $\nabla N_{WL} = \nabla N_1 - \nabla N_2$ is the double difference wide-lane ambiguity.

Equation (5) is substituted for equation (1), the float ambiguity resolutions of ∇N_1 and ∇N_2 are determined, and then many groups of integer ambiguity resolutions of ∇N_1 and ∇N_2 are searched using the LAMBDA method, as the equation(6), the final integer ambiguity resolutions are judged by the RATIO value and the residual sum of squares (SOSR), which the criteria are as follows[10]:

$$\begin{cases} Ratio > M \\ V_{LC}^{T} P V_{LC} = \min \\ (k\ \nabla N_2 + b) - \nabla N_1 < \delta \end{cases} \quad (6)$$

where M is a fixed limit deviation, which is usually 3.0, V_{LC} is the observation residuals of ionosphere free double difference combination, δ is a given positive tolerances, k and b represent processing values for the observation of carrier L_1 and L_2, and coordinate calculation.

2.4 The static Kalman filtering parameter estimation

When the parameters of the static GPS rapid positioning are estimated by the static Kalman filter, the state vector parameters don't change with time, so the state transition matrix of the static Kalman filter is $\boldsymbol{\Phi}_{k+1,k} = \boldsymbol{I}$. The troposphere delay correlation between the GPS reference stations and GPS island stations weakens with the increase of baseline length, so the troposphere delay residual influence can not be eliminated completely in the double difference observations, it must be estimated by the method of additional parameters. The Kalman filter state vector is:

$$\boldsymbol{X} = \begin{bmatrix} dX \\ \nabla N_{LC} \\ dT_1 \\ dT_2 \end{bmatrix} \quad (7)$$

where dX is the correction for the baseline vector, ∇N_{LC} is the double difference ambiguity vector of the free ionosphere combination, dT_1 and dT_2 represent the zenith troposphere delay in the reference station and the island station respectively.

3 GPS measurement and data analysis

To analyze positioning precision and reliability of cross-ocean GPS long distance rapid static positioning methods, GPS stations in Zhoushan and Xisha regions in China are selected to test the reliability and stability of the positioning method. Figure 1 and figure 2 present the distribution of observation stations in Zhoushan and Xisha respectively. The GPS processing strategy is shown in table 1.

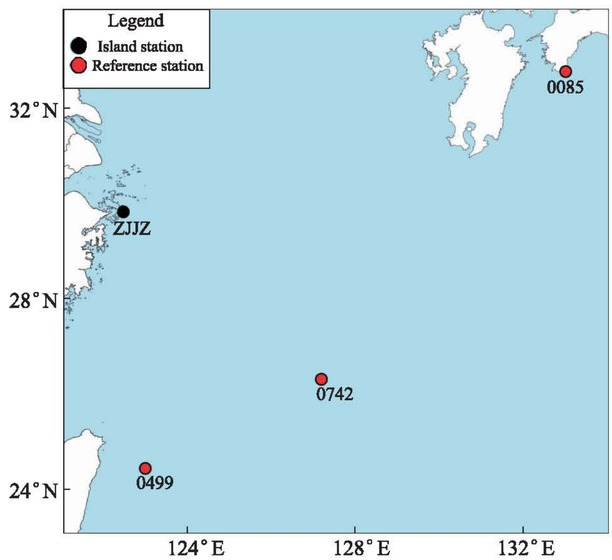

Figure 1 Position of the reference GPS stations and test GPS station in Zhoushan, China

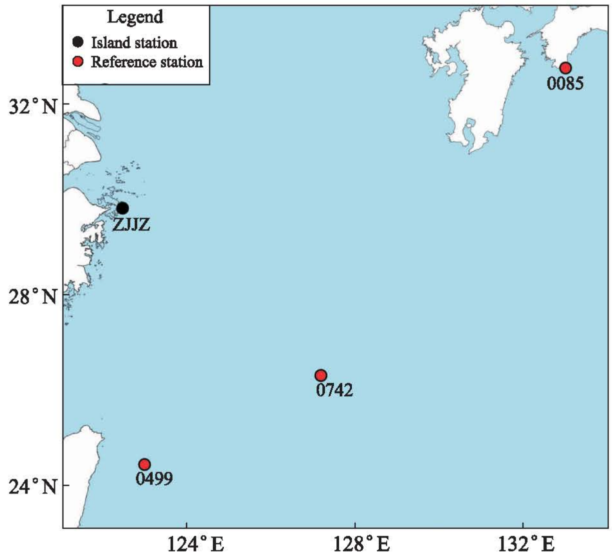

Figure 2 Position of the reference GPS stations and test GPS stations in Xisha, China

Table 1 GPS long distance processing strategy of rapid static positioning

No.	Parameters	Models
1	Ionosphere	Ionosphere-free combination
2	Orbit	IGS precision orbit
3	Troposphere	Troposphere parameter estimation
4	Cycle slip	Three difference observation
5	Data processing	The static Kalman filter
6	Integer ambiguity resolution	Wide-lane + LC
7	Coordinate calculation	Static parameters

GPS station ZJJZ (Zhujiajian) is choosen as the test station in Zhoushan, while the reference stations were three continuously operating reference stations (CORS) in Japanese CORS network: 0499, 0742 and 0085. The data used here were sampled during the period of July 28 to August 1 in 2010 (ftp://terras.gsi.go.jp/data/GPS_products/). The coordinates provided by Japanese Geographical Survey Institute on July 28 in 2010 were used as the reference coordinates of the reference stations. The reference coordinates of test stations were resolved by using the PANDA software with the GPS data on July 28 in 2010[11]. In Xisha region, the test stations were DDCZ (East Island) and NXSA (Yongxing Island) respectively. The data of DDCZ used here were sampled during the period of 07:23 to 22:59 on May 3 in 2011, while the data of NXSA used here were sampled during the period of 00:00 to 23:59 on May 3 in 2011. The reference stations were MMG and ZJGT in Guangdong CORS network and PIMO of IGS stations. The reference coordinates of test station and reference stations were resolved by using the PANDA software with the GPS data on May 3, 2011.

In order to verify the accuracy and reliability of the cross-ocean GPS long distance rapid static positioning respectively, the selected reference stations in Zhoushan and Xisha test areas were fixed, test station coordinates were computed using 1-hour data interval. The three-dimensional coordinates were used to analyze the coordinates variation compared with the reference coordinates. Three-dimensional errors of ZJJZ station, DDCZ and NXSA were obtained from relative positioning based on different baseline lengths, and the three-dimensional error distribution diagrams of ZJJZ station were drawn as shown by figures 3, 4 and 5. According to figure 3, three-dimensional errors of ZJJZ station fluctuate between 0 cm and 22 cm, but most are less than 7 cm, and the corresponding RMS (internal accord accuracy) is 4.3 cm. Figure 4 shows that three-dimensional error is 7.5 cm and the corresponding RMS is 4.26 cm. But in figure 5, there are five outliers: 1.18 m, 1.33 m, 1.29 m, 1.94 m and 1.07 m. When the outliers are removed, three-dimensional error is 9.3 cm and the corresponding RMS is 6.15 cm. These results demonstrate that three-dimensional accuracy of ZJJZ station decreases with increasing baseline distance. When cross-ocean baseline distance is about 600 km, the three-dimensional accuracy is not more than 7.5 cm and there are no outliers. However the baseline distance increasing to 1000 km, there are outliers in the three-dimensional error, which indicates the poor reliability.

The accuracy statistics of the three-dimensional coordinate errors of the three test sites in Zhoushan and Xisha are given in table 2. When the baseline lengths are not more than 650 km, the three-dimensional positioning errors of the three test stations are 10 cm or less using the cross-ocean GPS long distance rapid static positioning methods on a solution to the hourly data periods. However, with the increase of the baseline lengths, the reduction of public synchronous satellites,

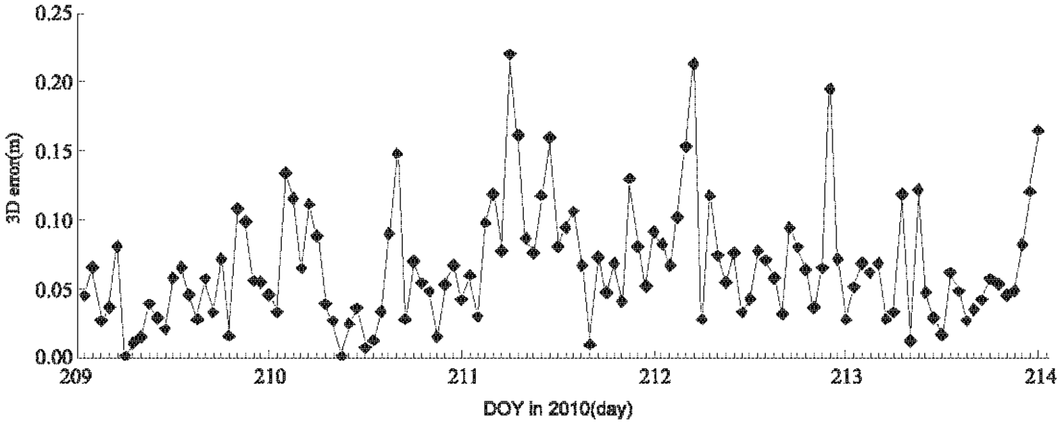

Figure 3 3D errors of ZJJZ station based on hourly solution of 0499-ZJJZ baseline

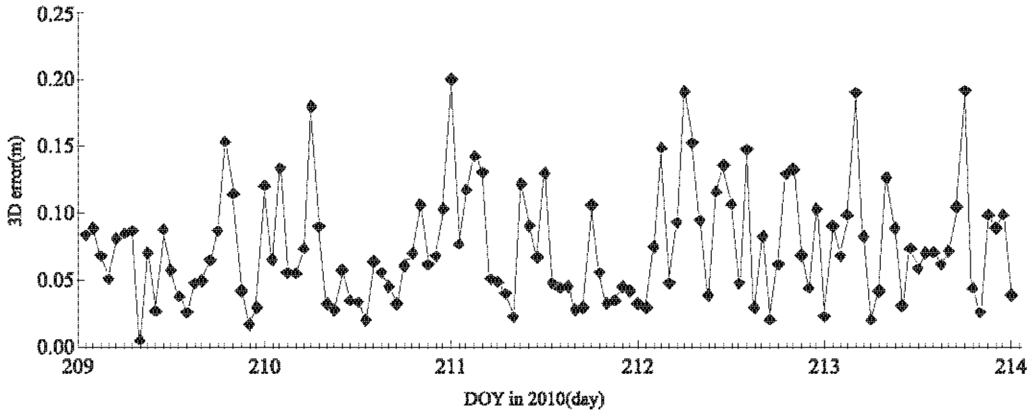

Figure 4 3D errors of ZJJZ station based on hourly solution of 0742-ZJJZ baseline

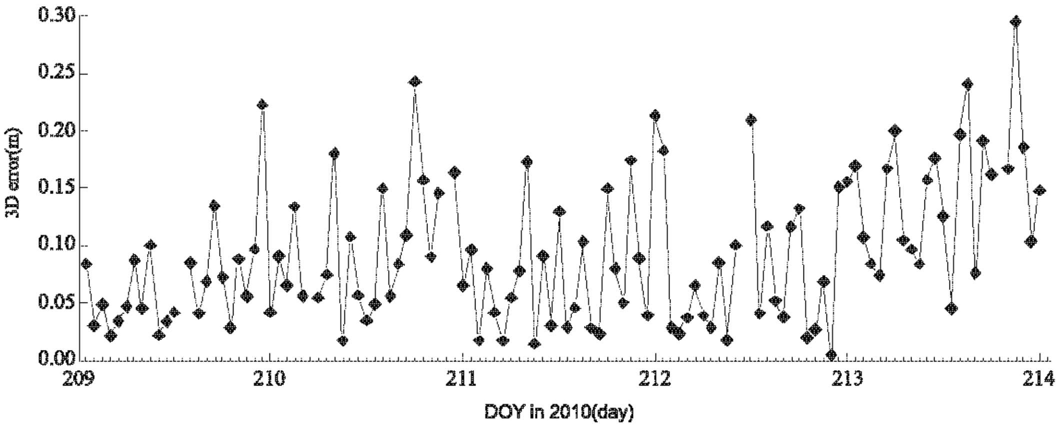

Figure 5 3D errors of ZJJZ station based on hourly solution of 0085-ZJJZ baseline

ionosphere and troposphere errors correlation leads to increase the three-dimensional errors. When the baseline length is about 1000 km, the three-dimensional error is 9. 3 cm at ZJJZ station in Zhoushan, but that is 12. 0 cm and 11. 3 cm respectively at DDCZ stations and NXSA station in Xisha. As can be seen from the above positioning results, three-dimensional error at ZJJZ station in Zhoushan is better than 10 cm when the baseline length is 1000 km, whereas the results in Xisha are greater than 10 cm when the baseline length

Table 2 3D Accuracy statistics of test stations in Zhoushan and Xisha

Region	Test station	Reference station	Baseline length (km)	3D errors (m)
Zhoushan	ZJJZ	0499	605	0.066
		0742	612	0.075
		0085	1050	0.093
Xisha	DDCZ	MMGT	591	0.099
		ZJGT	578	0.093
		PIMO	930	0.120
	NXSA	MMGT	650	0.100
		ZJGT	530	0.093
		PIMO	970	0.113

is over 650 km. From these analyses on the island positioning far from the mainland, marine atmospheric environmental condition is the main factor that causes the positioning accuracy.

4 Conclusions

The method of cross-ocean GPS long distance rapid static positioning has become one of the main technical means of GPS static positioning far from the mainland, which can satisfy the special data processing requirements in the complicated island environment. The test results in Zhoushan and Xisha show that static positioning accuracy is better than 10 cm using one-hour single baseline at the distance 500 – 600 km. If the baseline length is more than 650 km, the three-dimensional accuracy in Xisha is inferior to 10 cm. But when the baseline length is up to 1000 km, three-dimensional accuracy in Zhoushan is still superior to 10 cm. It shows that the atmospheric environmental impact in low latitude area is more complicated than that in middle latitude area. If the observation conditions permit, the positioning precision can be improved by increasing the observation time. The atmosphere influence need to be further studied in the case of special ocean environment in future research.

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