High-precision Ocean navigation with single set of BeiDou short-message device

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Abstract

The high-precision navigation and positioning with GNSS has become widely used in various applications with the development of new GNSS systems, such as BeiDou and Galileo. For marine applications, high-precision navigation and positioning with GNSS is still a challenge since the requirement of the communication link is a problem on sea. Both DGNSS and RTK require data communication between base station on land and the rover station on sea. The data communication can be performed by providers of the marine satellite communication service, such as Intelsat, Eutelsat, Telesat and the SpaceX etc. However the cost is too high to be afforded by ordinary GNSS users.

The BeiDou short message service provides an efficient way for the data communication between reference station on land and rover station on sea. Each BeiDou message length is limited to 78 bytes and the communication frequency is limited to 60 seconds. Based on the BeiDou short message service, the high precision positioning has been achieved in previous studies. However, multiple set of short-message devices are used and the cost is still high.

In this research, based on dual-frequency GNSS data, we propose the high-precision navigation on sea with single set of short-message device. The space-relative and time-relative positioning methods are integrated to reduce the data requirements. That is, first, every minute precise position is acquired with traditional space-relative positioning method and then the position of the other epochs is derived with time-relative positioning method. The experimental results based on buoy observations on sea show that the navigation accuracy can reach up to cm level in both horizontal and vertical directions. The proposed method can meet the requirements of different marine applications such as tide monitoring and wave monitoring.

Keywords: BeiDou, short-message, ocean navigation, time-relative, high-precision

1 Introduction

GNSS navigation and positioning has become more and more widely used in various land applications, especially with the launching of new GNSS systems in recent years, such as BeiDou and Galileo. However, for Ocean applications, high-precision navigation and positioning with GNSS is not very popular due to the limitation of data communication on sea. Both Differential GNSS (DGNSS) and Real-Time Kinematic (RTK) positioning, require data communication between base station and rover station. The most popularly used communication means on sea is the satellite communication provided by the companies including Intelsat, Eutelsat, Telesat and latest SpaceX (http://www.satmagazine.com/story.php?number=1152305751) etc. However, the cost is so high that the ordinary GNSS users cannot afford it.

The short message service is one of advantages of BeiDou system (BeiDou ICD, 2017). Through one of its Geostationary Satellites (GEO), we can send information to users on sea and the fee is very low. However, for civilian user, it has two limitations (CPBSM 4.0):

- Each BeiDou message length is limited to 78 bytes;
- The communication frequency is limited to 60 seconds.

Due to these limitations, the BeiDou short message cannot directly meet the requirement of the high-precision positioning with GNSS. Multiple short-message devices have been used to increase the bandwidth in previous studies (Yu et al, 2012; Li et al, 2017; Liu et al, 2017). However, multiple set of short-message devices are required and the cost cannot be afforded by ordinary users.

In this study, the high-precision positioning with the single set of short-message device is proposed. A new method is proposed to overcome the above mentioned two limitations. In this method, the space-relative and time-relative positioning methods are combined together. That is, first, every minute precise position is acquired with traditional space-relative positioning method (Liu et al, 2013) and then the position of the other epochs is derived with time-relative positioning method.

The rest of the paper is organized as follows. First, the measures to overcome the first weakness of BeiDou short message are introduced. Then, the method to overcome the second weakness of BeiDou short message is described. After that, the proposed procedures are tested based on practical buoy observations on sea. Finally, the conclusions are drawn.

2 Measures to overcome weakness No. 1 of BeiDou short message

In order to achieve the high-precision Ocean navigation with single set of BeiDou short-message device, GNSS data of one epoch is best to be finished sending in one short message. Since each short message contains 78 bytes at maximum, the measures must be taken to save the bandwidth.

2.1 Measures of simplifying corrections

As this research is based on dual-frequency GNSS data, as suggested in previous research (Li et al, 2017), in order to save space, only ionosphere-free phase and code corrections will be sent instead of four raw phase and code observations. The corrections can be calculated as follows (Leick, 2015).

$$\mathrm{d}\Phi_{r,IF}^{s} = \left(\rho_r^s + \lambda_{IF} N_{r,IF}^{s} + dR_r^s - \delta t_r^s + \tau_r + M_r^s Z_r^s + \varepsilon_{\Phi_{r,IF}^{s}}\right) - \Phi_{r,IF}^{s} \tag{1}$$

$$\mathrm{dP}_{r,IF}^{s} = \left(\rho_r^s + dR_r^s - \delta t_r^s + \tau_r + +M_r^s Z_r^s + \varepsilon_{\mathrm{P}_{r,IF}^{s}}\right) - \mathrm{P}_{r,IF}^{s} \tag{2}$$

Here, ρ_r^s is calculated geometric distance from receiver to satellite; dR_r^s and δt_r^s are satellite orbital and clock errors; τ_r is receiver clock error; $N_{r,IF}^{s}$ is ambiguity and λ_{IF} is corresponding wavelength; Z_r^s is tropospheric delay in zenith direction and M_r^s is mapping function; $\varepsilon_{\Phi_{r,IF}^{s}}$ and $\varepsilon_{\mathrm{P}_{r,IF}^{s}}$ are observations noise. And (Xu and Xu, 2016)

$$\Phi_{r,IF}^{s} = \frac{1}{f_1^2 - f_2^2}\left(f_1^2 \Phi_{r,1}^{s} - f_2^2 \Phi_{r,2}^{s}\right) \tag{3}$$

$$\mathrm{P}_{r,IF}^{s} = \frac{1}{f_1^2 - f_2^2}\left(f_1^2 \mathrm{P}_{r,1}^{s} - f_2^2 \mathrm{P}_{r,2}^{s}\right) \tag{4}$$

Here, $\Phi_{r,j}^{s}$ and $\mathrm{P}_{r,j}^{s}$ are the phase and code observations of frequency f_j.

Code corrections generally include receiver clock error, tropospheric delay error, satellite orbital and clock errors, multipath and observation noise etc. Among them, receiver clock error is generally the biggest. As it is common to all satellites, so in order to make the size as small as possible, the average is subtracted from code corrections as indicated in Eq. (5). The absolute values of simplified code corrections are generally no more than 10m.

$$\mathrm{d}\bar{\mathrm{P}}_{r,IF}^{s} = \mathrm{dP}_{r,IF}^{s} - \left(\sum_{s=1}^{n} \mathrm{dP}_{r,IF}^{s}\right)/n \quad (5)$$

Different from code one, phase correction includes one ambiguity parameter, which may possibly make phase correction very big. So first, all phase corrections of same satellite will be subtracted by the integer cycle of the first epoch and then the average is subtracted from them. Similar to code correction, the absolute values of simplified phase corrections are also generally no more than 10 m.

2.2 Data encoding

Each BeiDou short message only contains information of 78 bytes at maximum. To send as much data as possible within one short message, the data encoding is required. In this research, the encoding strategy is designed as follows.

Satellite PRN is encoded with one byte in this study. One byte with 8 bits can represent an integer ranging from 0 to 255. Since the number of any GNSS satellites is less than 40, one byte can represent more than 6 satellite systems when each integer is assigned to one PRN number. In this study, the PRN can be assigned according to Table 1.

Table 1 Encoding strategy for satellite PRN

GNSS	GPS	BeiDou	Galileo	GLONASS
range	1-40	41-80	81-120	121-160

One correction data, whether code or phase, is encoded with two bytes. With 16 bits, the largest number which can be represented is 1111111111111111, or 65535 in decimal notation. If a correction data is denoted as C (unit: m), the detailed encoding strategy will be $\mathrm{C} \times 1000 + 32768$. Thus, the correction range which can be encoded is from -32.768 m to 32.768 m. It means that if the correction is within the range, it will be sent, otherwise, it will not be sent. Practically, almost all correction data are within the range.

In this way, satellite PRN will take up one byte, correction data, whether code or phase, will take up 2 bytes, so one satellite data will take up 5 bytes. The sending of the observation time is unnecessary if it is on full minute, such as 00:00 and 01:00 as it can be easily deducted based on the receiving time. The other information to be sent may include the beginning mark of the message, the message length, the number of satellites and the parity check char etc. So one short message is able to send information of as many as 14 or 15 satellites, which is sufficient for high-precision positioning.

3 Method to overcome weakness No. 2 of BeiDou short message

As BeiDou short message can only be sent every minute, so high-precision positioning solution can only be achieved at epochs once in a minute with space-relative method. Such low sampling-rate solutions cannot meet requirements of most ocean applications. As such, it is important to get the precise positioning solution for other epochs.

In previous studies, a time-relative positioning method, shown in Figure 1, was proposed (Ulmer et al. 1995; Michaud and Santerre 2001; Balard et al. 2006; Odijk et al. 2007; Traugott et al. 2010). Distinct from the space-relative positioning method, this method performs differencing in the time domain and it requires only one GNSS receiver. To begin, the GNSS receiver is placed at station A to collect GNSS data for a short session. After that, it is moved to station B and records GNSS observations for another short session. Thus, the relative position between stations A and B can be calculated by performing time-differencing between the two sessions of GNSS data. If the coordinates of station A are precisely known, the absolute position of station B can also be determined.

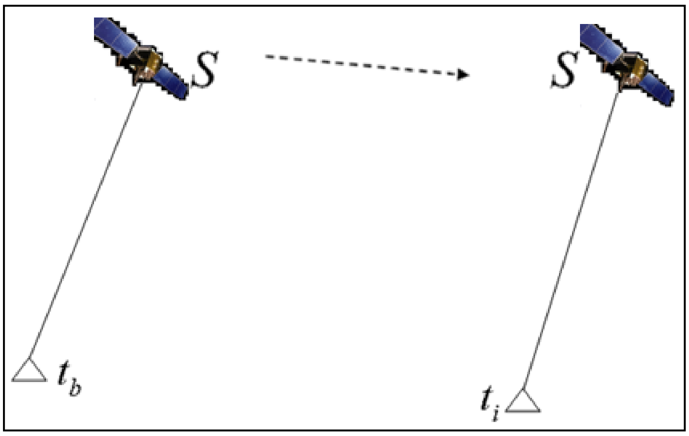

Figure 1 Principle of time-relative positioning method

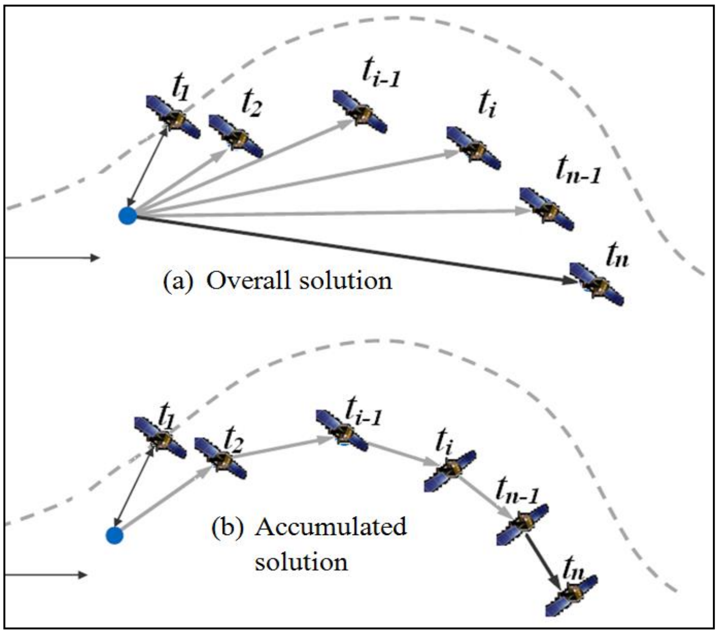

Figure 2 Overall time-relative method vs accumulated time-relative method

Compared with traditionally used space-relative method, the advantages of time-relative one are: only one GNSS receiver is required which is precisely the situation of our case, as between epochs with precise positioning solutions, only high-rate GNSS observations of rover receiver are available. Its disadvantage is that the positioning error may be much bigger than that in the space-relative method. This is because observations at two stations are not obtained simultaneously. Many time-variable errors in GNSS signals such as satellite-clock error, orbital error, and atmospheric error have a larger impact on the time-relative solution than on the space-relative solution from simultaneous observations. So the positioning accuracy degrades rapidly when the duration between stations A and B gets longer (Balard et al. 2006).

In recent years, another time-relative GNSS positioning method was proposed, which is called accumulated time-relative method and the previous one is then called overall time-relative method. Figure 2 is a comparison between them. The accumulated time-relative method can provide better positioning accuracy than the overall time-relative method (Traugott et al. 2010). The accumulated time-relative method will be used in this research to overcome weakness No. 2 of BeiDou short message and the detailed algorithms are introduced as follows.

Supposing the sampling rate of rover station is 1 Hz, there will be 60 observation equations in one minute:

$$\begin{gathered} A_0X_0 + BN + M_0Z = L_0 \\ A_1X_1 + BN + M_1Z = L_1 \\ \cdots\cdots\cdots \\ A_{i-1}X_{i-1} + BN + M_{i-1}Z = L_{i-1} \\ A_iX_i + BN + M_iZ = L_i \\ \cdots\cdots\cdots \\ A_{59}X_{59} + BN + M_{59}Z = L_{59} \end{gathered} \tag{1}$$

Eq. (1) are the linearized observation equations after differencing between satellites. X_i is the coordinate vector of rover station at epoch i, X_0 has been precisely acquired with space-relative method and X_1, X_2, …, X_{59} are unknown; N and Z are ambiguity vector and zenith tropospheric delay; A_i, B and M_i are corresponding coefficient; L_i is phase design vector.

Neglecting the difference between A_{i-1} & A_i and M_{i-1} & M_i and performing time-difference between equations of any two adjacent epochs, we can get:

$$\begin{gathered} A_0X_{0,1} = L_{0,1} \\ A_1X_{1,2} = L_{1,2} \\ \cdots\cdots\cdots \\ A_{i-1}X_{i-1,i} = L_{i-1,i} \\ \cdots\cdots\cdots \\ A_{58}X_{58,59} = L_{58,59} \end{gathered} \tag{2}$$

where $X_{i-1,i} = X_i - X_{i-1}$, and $L_{i-1,i} = L_i - L_{i-1}$.

With least-squares adjustment method, we can get:

$$\begin{gathered} X_{0,1} = (A_0^TP_0A_0)^{-1}A_0^TP_0L_{0,1} \\ X_{1,2} = (A_1^TP_1A_1)^{-1}A_1^TP_1L_{1,2} \\ \cdots\cdots\cdots \\ X_{i-1,i} = \left(A_{i-1}^TP_{i-1}A_{i-1}\right)^{-1}A_{i-1}^TP_{i-1}L_{i-1,i} \\ \cdots\cdots\cdots \\ X_{58,59} = (A_{58}^TP_{58}A_{58})^{-1}A_{58}^TP_{58}L_{58,59} \end{gathered} \tag{3}$$

Then, we can get the precise rover position of every epoch:

$$\begin{gathered} X_1 = X_{0,1} + X_0 \\ X_2 = X_{1,2} + X_1 \\ \cdots\cdots\cdots \\ X_i = X_{i-1,i} + X_{i-1} \\ \cdots\cdots\cdots \\ X_{59} = X_{58,59} + X_{58} \end{gathered} \tag{4}$$

4 Procedures of high-precision Ocean positioning with single set of BeiDou short-message device

Figure 3 gives the flowchart of high-precision Ocean positioning with single set of BeiDou short-message device.

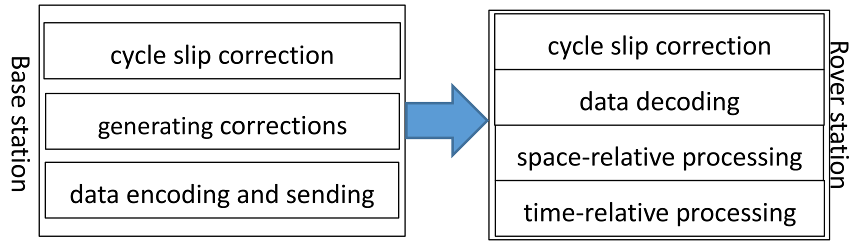

Figure 3 Complete procedures of high-precision Ocean positioning with single set of BeiDou short-message device

The cycle slip detection and correction is still a challenge for observations of one minute sampling interval. Therefore cycle slip must be repaired before sending phase corrections of base station. Then, corrections are generated based on known coordinates of base station. After that, the corrections will be encoded and sent to rover station through BeiDou short-message device.

Cycle slip of rover observations should be repaired first based on high-rate observations. After receiving the sending data from base station, the data are decoded. Then every minute precise position of rover station can be achieved with space-relative processing method. Finally, time-relative positioning method will be used to get high-rate precise rover position.

5 Experiment test

Two experiments are performed to evaluate the performance of the proposed method. First, the observations are collected and are then post-processed, but simulating real-time data processing, and finally, the results are presented.

5.1 Experimental setup

For the first experiment, a buoy (the left one in Figure 4) is placed in the Yellow Sea about 1 km from the shore and it is named BUOY. Then, a base station named SHOR is set up on the shore and another base station named SUST is set up on the top of a building in Shandong University of Science and Technology, QingDao, China. See Figure 5 (left) for the detailed positions of these three stations. The distance between SUST and BUOY is about 100 km. The receiver type of all the three stations is Trimble NETR5, which can collect observations of types C1, C2, L1 and L2 of GPS and GLONASS. The experiment time is on October 19, 2017 from 00:00:00 to about 06:30:00 (GPS time) and the sampling interval of collected observations is 1 second.

For the second experiment, the buoy and the base station on the shore are same, but the used observations are collected on October 20, 2017 and it is also from 00:00:00 to about 06:30:00 (GPS time). Another base station BXCS is set up in a village named Nanshanqian in Dalian city and the distance from BUOY to BXCS is about 350 km. See Figure 5 (right) for the detailed positions of these three stations. The receiver on BXCS is TPS NET-G3, the collected observation types are C1, C2, L1 and L2 of GPS and GLONASS and the sampling rate is 30 seconds.

Figure 4 Buoy in the Yellow Sea

Figure 5 Detailed positions of BUOY, SHOR, SUST and BXCS

For the first experiment, three baselines can be formed: BUOY-SHOR, SHOR-SUST and BUOY-SUST. For the second experiment, another three baselines can be formed: BUOY-SHOR, SHOR-BXCS and BUOY-BXCS. In both experiments, the first baseline is a short one about 1 km. For its processing, first, form double-differencing observations; and do outlier detection and cycle slip detection & repairing; then, form every epoch observation equations; after that, with Gauss Elimination method, remove coordinate parameters from every observation equation and only ambiguity parameter remains; with Sequential Adjustment method, get the float ambiguity solution and fix them with a F-ratio test (threshold value: 2); finally, with the fixed ambiguity solution, get every epoch coordinate solution. So after above processing, every epoch precise relative position between BUOY and SHOR are acquired. In both experiments, the second baseline is composed with two static stations and the data is processed with Bernese 5.0 software. With observations of more than 6 hours, the accuracy of the relative position can reach mm level. As in both experiments, the three baselines can form a closure, so the positioning accuracy of BUOY-SUST and BUOY-BXCS can be checked with the results of the other two baselines.

5.2 Data processing

Though the processing of the baseline BUOY-SUST and BUOY-BXCS is post-processed, real-time processing is simulated according to the proposed procedures in Figure 3.

Cycle slips of station SUST, BUOY and BXCS observations are detected and corrected respectively first, then the ionosphere-free code and phase corrections of SUST and BXCS, at epoch time 00:00:00, 00:01:00, 00:02:00, …., are calculated, encoded and sent through BeiDou short-message device (Figure 6) every minute. Only satellites with elevation angle higher than 15° are used and the number is no more than 14.

Figure 6 BeiDou short-message device

After receiving the sending data through BeiDou short message, the rover station will do the following processing. As the time delay of data sending is generally no more than 2 seconds, based on the receiving time, it is easy to determine the epoch time of the received corrections. So first form observation equation by applying the received corrections $\mathrm{d}\Phi_{b,IF}^{s}$ and $\mathrm{dP}_{b,IF}^{s}$.

$$\begin{cases} \mathrm{d}\Phi_{b,IF}^{s} + \Phi_{u,IF}^{s} = \mathrm{A}_{u}^{s}X_{u} + \tau_{u} + M_{u}^{s}Z_{u}^{s} + \lambda_{IF}N_{u,IF}^{s} \\ \mathrm{dP}_{b,IF}^{s} + \mathrm{P}_{u,IF}^{s} = \mathrm{A}_{u}^{s}X_{u} + \tau_{u} + M_{u}^{s}Z_{u}^{s} \end{cases}$$

Here, X_u is buoy position and A_{u}^{s} is corresponding coefficient; $\Phi_{u,IF}^{s}$ and $\mathrm{P}_{u,IF}^{s}$ are ionosphere-free phase and code design vector; τ_u is buoy receiver clock error; Z_{u}^{s} is buoy zenith tropospheric delay and M_{u}^{s} is mapping function; $N_{u,IF}^{s}$ is ionosphere-free ambiguity and λ_{IF} is the corresponding wavelength.

Then form observations equation between satellites (Leick, 2015):

$$\begin{cases} \widetilde{\Phi}_{u,IF}^{pq} = \mathrm{A}_{u}^{pq}X_{u} + M_{u}^{pq}Z_{u}^{pq} + \lambda_{IF}N_{u,IF}^{pq} \\ \widetilde{\mathrm{P}}_{u,IF}^{pq} = \mathrm{A}_{u}^{pq}X_{u} + M_{u}^{pq}Z_{u}^{pq} \end{cases}$$

After that, Kalman filter is applied to get the buoy coordinates (Mobinder et al, 2013). Note that the coordinates can only be acquired every minute. Finally, time-relative method is used to get the buoy position of the other epochs.

5.3 Numerical results

In this section, the numerical results of the two experiment tests are presented in different directions. For the first experiment test, a data outrage case is simulated and the resulting positioning error is investigated.

5.3.1 Numerical test 1

As mentioned in Section 1, the coordinate error of closure between these three baselines BUOY-SUST, BUOY-SHOR and SHOR-SUST can be used to check the accuracy of SHOR-SUST, which is presented in the following figures. In addition, the positioning results of one-minute sampling interval is compared to the case of one-second in order to show the effect of different sampling rates on positioning.

Figures 7, 8 and 9 show the positioning errors in X, Y and Z directions. We can see that the positioning results of one-minute and one-second are generally consistent especially after the duration of one hour. The positioning errors are generally no more than 5 cm in X and Z directions. In Y direction, the positioning errors are much bigger, but generally they are no more than 10 cm.

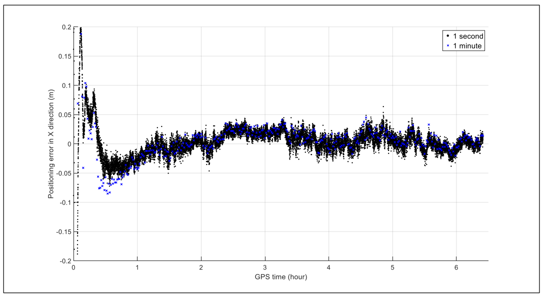

Figure 7 Positioning error in X direction (one-second vs one-minute)

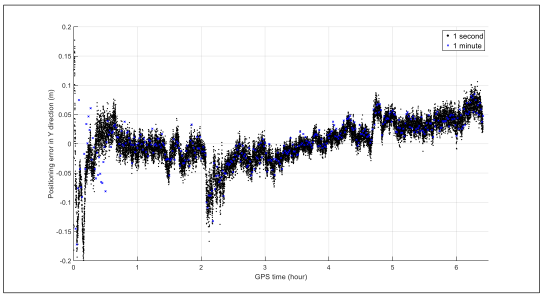

Figure 8 Positioning error in Y direction (one-second vs one-minute)

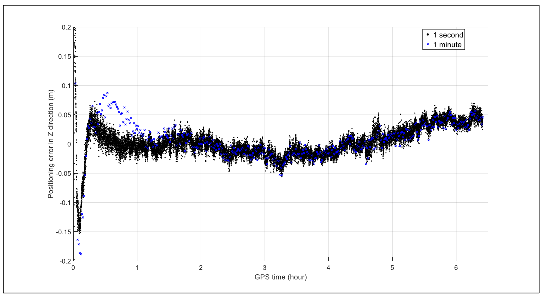

Figure 9 Positioning error in Z direction (one-second vs one-minute)

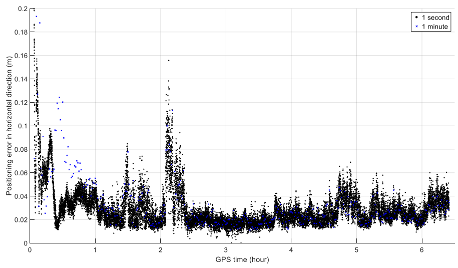

Figure 10 Positioning error in horizontal direction (one-second vs one-minute)

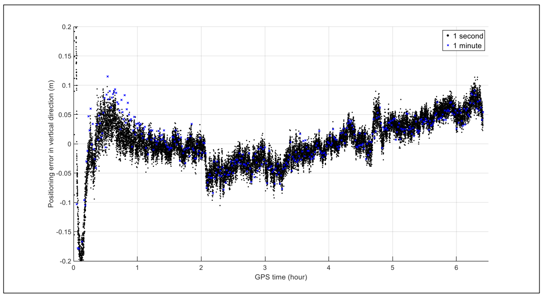

Figure 11 Positioning error in vertical direction (one-second vs one-minute)

Figures 10 and 11 show the positioning errors in horizontal and vertical directions. We can see that the positioning results of one-minute and one-second are also generally consistent especially after the duration of one hour. The positioning errors are generally no more than 5 cm in horizontal direction. In vertical direction, the positioning errors are obviously bigger, but they are generally no more than 10 cm.

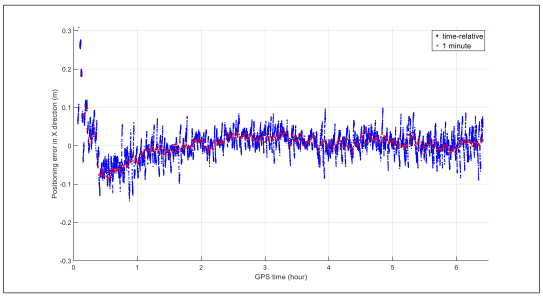

Figure 12 Positioning error in X direction with time-relative method

Figures 12, 13 and 14 show the positioning errors in X, Y and Z directions with time-relative method. The red are every minute positioning error from space-relative method and the blue are the positioning error from time-relative method. We can see that the accumulated errors with time-relative method are obvious, but they are generally no more than 10 cm in X and Z directions and in Y direction, the positioning errors are a little bigger and can be more than 10 cm occasionally.

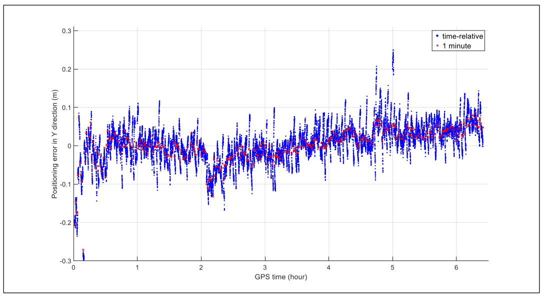

Figure 13 Positioning error in Y direction with time-relative method

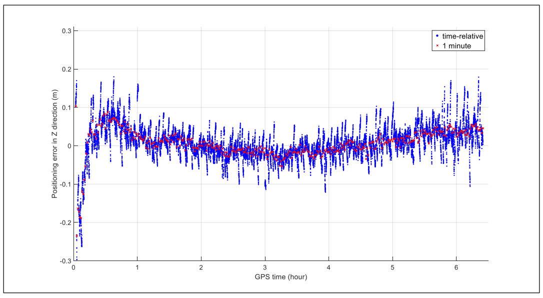

Figure 14 Positioning error in Z direction with time-relative method

Figure 15 and 16 shows the positioning errors in horizontal and vertical directions with time-relative method. We can see that the accumulated errors with time-relative method are obvious, but most of the positioning error are no more than 10 cm in horizontal direction and the RMS value is about 3.8 cm. In vertical direction, the positioning errors seem a little bigger, sometimes they can be more than 20 cm and the RMS value is about 5.5 cm.

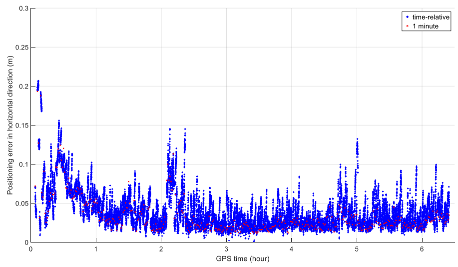

Figure 15 Positioning error in horizontal direction with time-relative method (RMS: 3.8 cm)

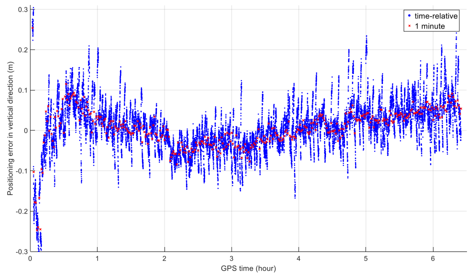

Figure 16 Positioning error in vertical direction with time-relative method (RMS: 5.5cm)

Same to other communication means, BeiDou short message may also have interruption occasionally. In case of data outrages from base station, rover station has to get real-time position through cumulating movements between epochs by time-relative method or by Standard Point Positioning. An investigation is carried out by simulating an outrage of every 15 minutes. Figure 17 shows the positioning error by cumulating movements between epochs for every outrage. We can see that with the increase of outrage time, the positioning error increases dramatically, especially in vertical direction, which can reach more than 1 m. While in horizontal direction, for outrages of 5 minutes, the positioning errors will generally not exceed 0.2m, and for outrages of 15 minutes, it will not exceed 0.5m generally.

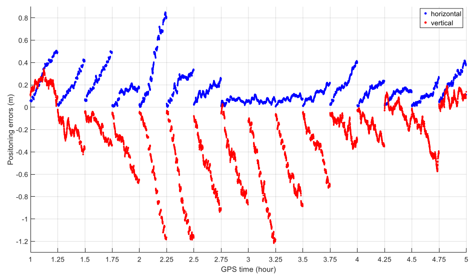

Figure 17 Data outrage investigation

The reason why the positioning accumulating so rapidly is mainly due to some systematic errors. For example, as the time-relative method is based on single receiver, orbital error and satellite error cannot be removed. In addition, there are other errors, for example, when forming Equation (2) from Equation (1), the difference of design matrix between neighboring epochs is neglected and it can cause error.

5.3.2 Numerical test 2

Similar to the first experiment, for the second experiment, the coordinate errors of closure between these three baselines BUOY-BXCS, BUOY-SHOR and SHOR-BXCS are used to check the accuracy of SHOR-BXCS and are presented in the following figures.

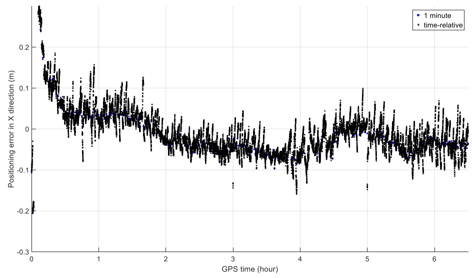

Figure 18 Positioning error in X direction with time-relative method

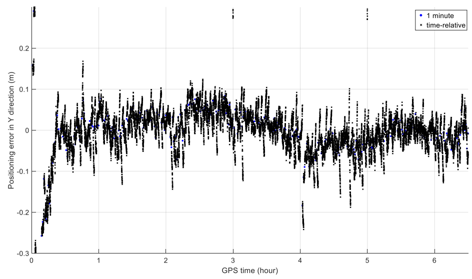

Figure 19 Positioning error in Y direction with time-relative method

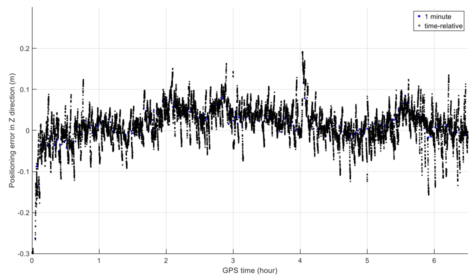

Figure 20 Positioning error in Z direction with time-relative method

Figures 18, 19 and 20 show the positioning errors in X, Y and Z directions with time-relative method. The blue are every minute positioning error from space-relative method and the black are the positioning error from time-relative method. We can see that the accumulated errors with time-relative method are obvious, but they are generally no more than 10 cm in these three directions.

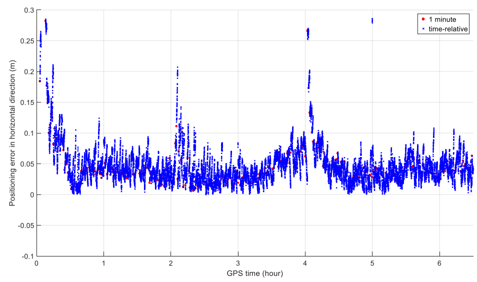

Figure 21 Positioning error in horizontal direction with time-relative method (RMS 5.1cm)

Figure 21 and 22 shows the positioning errors in horizontal and vertical directions with time-relative method. We can see that the accumulated errors with time-relative method are obvious, but most of the positioning error are no more than 10 cm in horizontal direction and the RMS value is about 5.1 cm. In vertical direction, the positioning errors are generally no more than 10 cm and the RMS value is about 5.9 cm.

Compared to the first experiment, though the baseline length of the second experiment is much bigger, about 350 km, we can see that the positioning accuracy is similar to that of the first experiment or the positioning accuracy is only slightly worse than that of the first experiment.

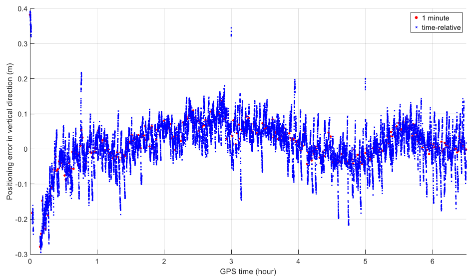

Figure 22 Positioning error in vertical direction with time-relative method (RMS 5.9 cm)

6 Conclusions

In this research, a complete procedures are proposed for high-precision Ocean navigation with single set of BeiDou short message device. The most outstanding feature with the proposed procedures is that time-relative method is applied to overcome the second weakness of BeiDou short message, i.e., information can only be sent every minute.

An experiment is designed based on the practical buoy observations and by simulating real-time data processing. The numerical results show that:

- The positioning results are consistent between the two cases: one-minute and one-second sampling intervals;
- The one-minute positioning errors are generally no more than 5 cm in horizontal direction and no more than 10 cm in vertical direction;
- The accumulated error with time-relative method is obvious, but in horizontal direction, most of the positioning errors are no more than 10 cm in both horizontal and vertical directions and the RMS value for both directions are about 5 cm.

Currently, the cost of one BeiDou short-message device is about 5600 CN¥ (about 1375 US$) and the annual BeiDou short-message communication fee is only about 1100 CN¥ (about 275 US$), much cheaper than TerraStar-C subscrition service, with which the fee is about $810,00 for one year in 2015 (High accuracy receivers and subscription services – 2015 Sales Meeting, 2015). So with the proposed procedures in this research, an ordinary user can afford to realize high-precision Ocean navigation.

For some Ocean environmental monitoring applications, such as tide monitoring and wave monitoring etc, cm level positioning accuracy is required generally. So the proposed method in this research may meet the accuracy need of these applications.

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References

Balard N, Santerre R, Cocard M, Bourgon S (2006) Single GPS receiver time-relative positioning with loop miscloure corrections. GPS Solutions, Vol. 10, No. 1: 56–62.

BeiDou Navigation Satellite System Signal In Space Interface Control Document (2017) http://www.beidou.gov.cn/xt/gfxz/201712/P020171218337008148266.pdf

Communication protocol of BeiDou short message (CPBSM), version 4.0. https://www.bdstar.com

Leick A (2015) GPS Satellite Surveying, 4th Edition. John Wiley and Sons, New York.

High accuracy receivers and subscription services – 2015 Sales Meeting (2015). https://agronaplo.hu/files/2015/11/gnss-subscription-services.pdf

Li BF, Zhang ZT, Zang N, Wang SY (2017) High-precision GNSS ocean positioning with BeiDou short-message communication. Journal Of Geodesy, https://doi.org/10.1007/s00190-018-1145-z.

Liu H, Wan LJ, Lu YY (2017) High precision positioning technology for long distance ocean engineering based on BeiDou Satellite Navigation System. Bulletin of Surveying, No. 5: 62-66.

Liu ZZ, Ji SY, Chen W, Ding X (2013) New fast precise kinematic surveying method using a single dual-frequency GPS receiver. Journal of Surveying Engineering, Vol. 139, No. 1, https://doi.org/10.1061/(ASCE)SU.1943-5428.0000092

Michaud S, Santerre R (2001) Time-relative positioning with a single civil GPS receiver. GPS Solut 5(2):71–77.

Mohinder SG, Angus PA, Chris GB (2013) Global Navigation Satellite Systems, Inertial Navigation, and Integration. 3rd Edition, John Wile & Sons, Inc., Hoboken, New Jersey.

Odijk D, Traugott J, Sachs G, Montenbruck O, Tiberius C (2007) Two precision GPS approaches applied to kinematic raw measurements of miniaturized L1 receivers. In: Proceedings of ION GPS-2007, Fort. Worth, Texas.

Traugott J, Holzapfel F, Sachs G (2010) Conceptual approach for precise relative positioning with miniaturized GPS loggers and experimental results. From: https://www.sto.nato.int/publications/STO%20Educational%20Notes/RTO-EN-SET-116-2010/EN-SET-116(2010)-04.pdf, accessed on 1 February 2010.

Ulmer K, Hwang P, Disselkoen B, Wagner M (1995) Accurate azimuth from a single PLGR+GLS DoD GPS receiver using time relative positioning. In: Proceedings of ION GPS-95, Palm Springs, California, pp 1733-1741.

Xu G and Xu Y (2016) GPS theory, algorithms and applications. Springer, Berlin.

Yu LY, Wang X, Li SJ (2012) Positioning data compression and reliable transmission based on BeiDou short message. Journal of Electronic Technology Applications, Vol. 38, No. 11: 108-111.