Monitoring Tides with GNSS Buoys in Open Sea Areas

Weikang Sun [1,2], Xinghua Zhou[1,2,*], Yanguang Fu [1,2], Zhaoyang Wang[3] and Dongxu Zhou[2]
[1]*College of Geomatics, Shandong University of Science and Technology, Qingdao, 266590, China;*
[2] *First Institute of Oceanography, State Oceanic Administration, Qingdao, 266061, China.*
[3] *National Marine Information Center,Tianjin, 300171, China*
Email: xhzhou@fio.org.cn

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Abstract: Nowadays, the coastal tide observation technology has developed very well. However, there still lacks a reliable and quick method of acquiring tidal level in open sea areas. To overcome this problem, a GNSS buoy has been developed, which is equipped with data acquisition system and shore station system. Also, some tidal level extraction algorithms are also proposed. Based on Precision Point Positioning, the GNSS data is calculated. Kalman filtering, attitude correction, smoothing, and sampling are performed on the high-frequency GNSS solution results. And the above results are corrected using the prior periodic information. The tidal level derived from the GNSS buoy without and with prior periodic information are compared with the tidal level derived from the regional tide model (NAO.99Jb). The RMSE are 7.6cm and 4.8cm, respectively. Also, the tidal level derived from the GNSS buoy with prior periodic information in spring tide period are less accurate than it in neap tide period. The RMSE are 6.4cm and 3.7cm, respectively. The results show that GNSS buoy can provide high accuracy tidal level.

1 INTRODUCTION

At present, marine observation buoys have developed rapidly and maturely, including wave buoys, tsunami buoys (Kato et al., 2008) and so on. GNSS buoys are a new type of marine surveying instrument that has emerged with the rapid development of GNSS satellite positioning technology since the early 1990s. It can obtain high precision tidal level and carry out the correction of the sounding in the offshore areas. It is of great significance for the construction of the channel and the safety of the navigation. The measurement principle of GNSS buoys is to obtain the precise spatial geocentric coordinates of the phase center of the GNSS antenna through GNSS Real Time Kinematics(RTK), post-processing kinematics(PPK) or precise point positioning (PPP). Then combined with the measured height of the center of the antenna's phase relative to the water surface, a time-sampling sequence of the height from the sea surface to the reference ellipsoid can be obtained. The GNSS buoy measurement principle is shown in Figure 1 (Bisnath, 2004):

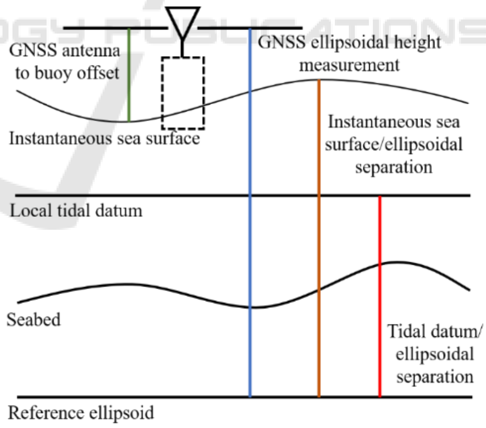

Figure 1: The principle of GNSS buoy measurement.

When using the GNSS buoy to observe the water level, the GNSS buoy elevation observation data has a lot of noise due to the influence of the GNSS observation error, the sea wave, the change of the buoy attitude and so on (Bisnath, 2004). At present, the GNSS observation error can be effectively eliminated by using a perfect model and method

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(Hein et al., 1992; Kelecy et al., 2011), and the error of the buoy attitude change can be eliminated by the attitude correction. Therefore, eliminating the influence of ocean waves in GNSS buoy height data is particularly important. In distant sea areas, changes in the attitude of the carrier caused by wind waves will bring greater errors to the tide measuring (Yang and Zhao, 2003; Zhao et al., 2006). The attitude correction technology can reduce the error effect caused by severe shaking of the carrier to the tide inspection. The PPK or PPP mode is not limited by radio signal transmission and can further expand the tide measuring range. Therefore, PPK or PPP mode can be considered for tide measuring combined with attitude parameters in the offshore areas.

Aiming at these problems, a combined GNSS buoy was developed and a new algorithm for extracting tidal information was proposed.

2 BUOY DEVELOPMENT

The GNSS buoy is mainly composed of two parts: data acquisition system and shore station system.

The data acquisition system includes an embedded data collector, a high-precision attitude sensor, a high-accuracy GNSS module, a Beidou transmit signal module, a power supply voltage regulator module, and a corresponding software system. The system can be operated independently to collect raw observations of GNSS tidal level measurements. The GNSS receiver is an independently developed multimode and multi frequency data acquisition device with the NOV703GGG.R2 antenna. The TCM2.5 attitude instrument is integrated inside the system and is used to measure the instantaneous roll, pitch and heave, providing attitude correction parameters for the GNSS tidal data. The data collector of the buoy is installed in the buoy cabin, and the GNSS antenna and Beidou satellite terminal are installed on the bracket at the buoy platform.

The shore station system includes the Beidou reception signal module, data monitoring module, and data preprocessing module. The system is used to monitor the operational status of the buoy, such as buoy position information, attitude information and the working status of each module.

3 INTRODUCTION OF OPEN SEA EXPERIMENT

Before the GNSS buoy was placed to the measuring areas, the elevation of the antenna should be calculated first.

A dynamic calibration method of measuring GPS buoy antenna elevation based on GPS PPK and synchronous tide observation data was adopted (Zhou et al., 2015). After installing and debugging the GNSS buoy system, the base station was set up at the wharf, which was about 20m from the GNSS buoy. At the same time, a pressure tide gauge was installed at the same site with the base station to observe the tidal level. Combined with three CORS stations of Shipu, Dongshan and Kanmen in the coastal GNSS observation network, the three-dimensional coordinates of the base station under the framework of ITRF2008 were obtained. Using the synchronous observation data from the base station, the dynamic coordinates of the GNSS buoy antenna phase center are solved one epoch by one epoch with the using of the Differential method. The tidal level recorded by the tide gauge was converted to geodetic height. The GNSS buoy's dynamic antenna elevation was processed by a moving average method, and the tidal level of geodetic height recorded by the tide gauge was subtracted. Then the GNSS buoy dynamic antenna elevation can be obtained.

After completing the buoy antenna elevation measurement, the buoy was placed in the East China Sea for continuous observation of tidal level (shown in Figure.2).

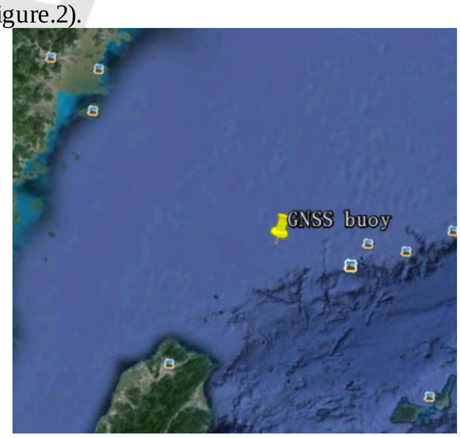

Figure 2: The distribution of reference stations and GNSS buoy.

4 DATA PROCESSING

4.1 GNSS Data Processing Based on PPP Technology

The PPP location technology does not require a reference station. Single epoch-precise single point positioning is performed after initialization with the using of the non-differential dual-frequency carrier phase observations. Using post-processing mode, the precise ephemeris and clock difference files provided by IGS were selected, and then the phase or pseudo-range observations collected by a single receiver were subjected to non-differential positioning processing.

4.2 Tidal Level Extraction

We developed a three steps procedure to extract the actual tidal level from the GNSS data and to subsample the data from 1sec intervals to 1min interval. The data processing of the GNSS buoy is performed by PPP technology, and the series of the antenna phase center elevation is obtained.

4.2.1 Kalman Filtering

The best estimation criterion of the Kalman filtering is the minimum mean square error, which requires that the optimal estimation of the signal or state should have the smallest error variance from the corresponding true value. The basic idea is to use the state space model of signal and noise, update the estimation of the state variables with the estimates of the previous time and the observations at the current moment, and find the estimated value at the moment of occurrence. Kalman filtering is an efficient recursive filter that can estimate the state of a dynamic system from a series of measurements that do not completely contain noise.

4.2.2 Intermediate Data Subsampling and Smoothing

In this step, the GPS raw data is subsampled at 1minute intervals. From this subsampled series, records are smoothed by a 60minute average window (Apel et al., 2012). The smoothing is performed bi-directionally over the time series in order to prevent phase shifts.

4.2.3 GNSS Buoy Data Processing with Prior Periodic Information

With the rapid development of modern geodetic technology, measuring methods are becoming more and more advanced, and geodetic data has become more and more abundant. Our understanding of the geometric, physical and mechanical properties of any observing target or object is also becoming more and more sufficient, and the possibility of establishing periodic based on prior information is increasing. In the technique of extracting tidal information from GNSS buoys, we know the period information of each constituent, instantaneous tidal level can be expressed as (Huang and Huang, 2005):

$$\zeta(t)=\sum_{j=0}^{n}(A_j\cos\sigma_j t+B_j\sin\sigma_j t)+x(t) \tag{1}$$

Where, $\zeta(t)$ represent GNSS buoy-derived time series; n is the number of constituents; σ is the angular rate of constituents; t is time; $x(t)$ is non-astronomical tidal level and A、B are coefficient matrixes waiting to be solved.

Taking into account the time length of $\zeta(t)$, the appropriate constituents should be selected and the coefficient matrix of A、B can be solved. $x(t)$ can be obtained by polynomial fitting. Through the obtained coefficient matrix A、B, non-astronomical tidal level $x(t)$, and known constituents periodic information, the new $\zeta(t)$ can be obtained, which is the tidal level extracted from the GNSS buoy after corrected by the prior periodic information. The tidal level terms are long-period items, the period is generally several hours to ten hours; the surge-wave items are short-wave items, and the period is generally tens of seconds to tens of minutes. The influence of short period surge-wave can be eliminated by selecting the appropriate tide.

5 RESULTS AND DISCUSSION

The PPP calculation results for a single day are shown in Figure 3. 7 April was chosen, as it was a representative sample of the entire dataset. The data set is referenced to WGS84 ellipsoid.

As suggested in Figure 3, the processing filter noise was a high frequency signal riding upon the lower frequency water level changes. After Kalman filtering, most of the gross errors were eliminated, as shown in Figure 4.

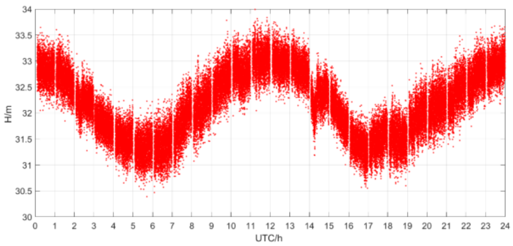

Figure 3: GNSS buoy height solutions for 7 April 2016.

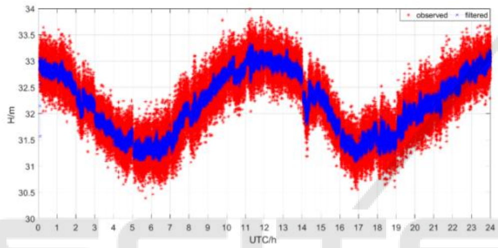

Figure 4: GNSS buoy height solutions and filtered data for 7 April 2016.

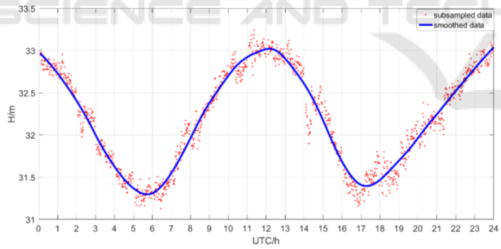

Figure 5: Subsampled and smoothed GNSS buoy height solutions for 7 April 2016.

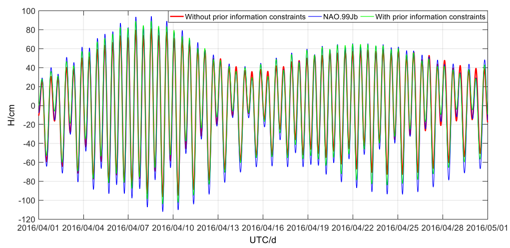

Figure 6: GNSS buoy height solutions verses NAO.99Jb for the entire month of April.

The data in April was processed day-by-day according to the above steps, and the overall results for April were obtained. Then, the prior information was used to correct the overall results in April. The reference datum was transformed from WGS84 ellipsoid to monthly mean sea level. Compare the two results with NAO.99Jb, as shown in Figure 6.

Since the GNSS buoy was far away from the mainland and there was no tide gauge station in the surrounding area, the NAO.99Jb tidal model was selected to verify the accuracy of GNSS buoys for measuring tidal level. The NAO.99Jb tidal model is a regional tidal model constructed by the Japanese National Observatory based on two-dimensional nonlinear equations using the Blending assimilation method (Matsumoto et al., 2000). Compared with other global models, NAO.99Jb has the highest accuracy in the layout areas of the buoy (Fu et al., 2017) .

Figure 6 shows that the tide data without prior information periodic are less accurate than the tide data with prior information periodic compared with the NAO.99Jb. The RMSE is 7.6cm and 4.8cm, respectively. The RMSE is defined as (Lin et al., 2017):

$$RMSE = \sqrt{\frac{1}{N}\sum_{t=1}^{N}(y_t - \hat{y}_t)^2} \quad (2)$$

where, y_t and $\hat{y}_t$ represent the tides obtained from the regional tide model NAO.99Jb and the GNSS buoy, respectively, and N is the number of tide data.

It is proved that the tidal level correction based on priori periodic information has a great contribution to improving the accuracy of GNSS buoys for extracting tidal information. Notably, the amplitude of the GNSS buoy height solutions is smaller than it of NAO.99Jb. A possible reason is the inclination of the GNSS buoy (Lin et al., 2017). Another possible reason is that the bathymetry model that the NAO.99Jb used are not accuracy enough, which affect the tidal level calculation.

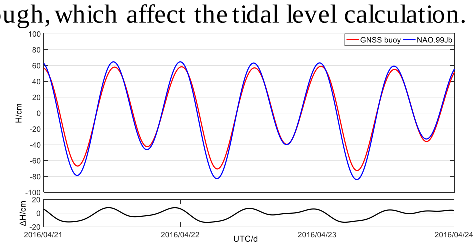

Figure 7: GNSS buoy height solutions with prior periodic information verses NAO.99Jb for the spring tide.

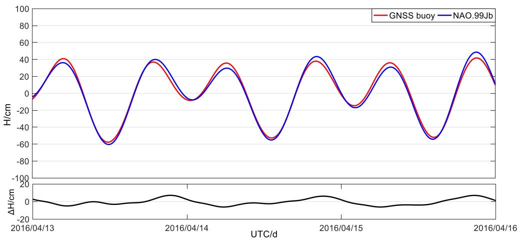

Figure 8: GNSS buoy height solutions with prior periodic information verses NAO.99Jb for the neap tide.

As can be seen from Figure 7 and Figure 8, the tide period measured by the GNSS buoy is in good agreement with the model. The accuracy in spring tide period is lower than it in neap tide period. The RMSE is 6.4cm and 3.7cm respectively.

6 CONCLUSIONS

Using GNSS technology to measure tidal level is a new measurement method. This article introduces in detail the measurement of tidal level in coastal areas and open sea with the using of the modular GNSS buoy.

By making full use of the precise three-dimensional dynamic measurement technology of precise point positioning, it is possible to measure tidal level in areas where traditional methods are difficult to perform and in open sea areas. Through a series of processing to the elevation of the antenna, such as Kalman filtering, attitude correction, smoothing, subsampling and adding prior periodic information correction, the time series of tidal level with the accuracy of cm level can be obtained.

The open sea GNSS buoys have high observation accuracy, and the deployment is not limited by sea and land conditions. If long-term effective observations are carried out, reliable tidal level information can be obtained. On the one hand, it is possible to supplement the tidal data with the construction of a global tidal model to improve its construction accuracy. On the other hand, the GNSS buoy can be used to calibrate the altimeter directly at the sub-satellite point. This method is not affected by tidal models and geoid and it and is widely used in the study of altimeter calibration (Bonnefond et al., 2003).

The prospect of the application of buoys is to realize the extraction of real-time tidal level, further investigation is required to resolve the discrepancies between the real-time and post-processed solutions. We should give full play to the applicability and expandability of GNSS buoy technology in marine surveillance in the near future.

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