Monitoring the Study of Offshore Sea Level Changes with GPS-MR Technology

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Abstract. The monitoring of sea level change is a hot issue in the field of marine environment and global climate change research. With the rapid development of GNSS theory and application, GPS-MR technology based on multipath effect has been proved by scholars to be used for tidal level monitoring. In order to further expand the application space of GPS-MR technology in the field of marine environment monitoring, this paper conducts research on offshore sea level change based on tidal level change data acquired by GNSS-MR. This paper first gives the calculation process of GPS-MR technology to obtain the daily average sea surface, and then obtains the high-precision daily average sea surface and month by using the measured data of GNSS at different time intervals and different frequencies on the shore of the Harbour Harbor in Washington, USA. The average sea surface is in good agreement with the results of the tide check station. The experimental results show that GPS-MR technology has higher precision for obtaining tidal level change and regional mean sea surface change, and lays a foundation for GPS-MR technology to supplement satellite altimetry for offshore sea level change and to carry out offshore sea tide model refinement.

Keywords: GPS multipath reflection · SNR · Tidal level change · Daily average sea surface

1 Introduction

Sea level is a very sensitive indicator of climate change that reflects the components of the climate system, such as heat, melting of glaciers and ice sheets. Sea level rise poses enormous challenges and threats to human survival and economic development in coastal areas. Monitoring sea level changes not only plays an important role in understanding the climate, but also helps to understand the social and economic

consequences of sea level rise. The relationship between tides and navigation is also very important. It will directly affect the implementation of the navigation plan and the safety of navigation. If it is necessary to pass the shallow water area, it is necessary to calculate the local tide height and tide time based on the tide data and adjust the draft difference correctly; Sailing safely on planned routes requires constant knowledge of local tides and trends. Even in Hong Kong, it is impossible to ignore the impact of tides and trends on ship safety. In the coastal navigation, the captain's navigational order, the company's navigational rules and regulations, and the guiding documents of the international organization's pilots on the navigational watch will all be aware of the current and future tides and tides as the safe work of the bridge important content [1–4].

As early as the beginning of the 21st century, the interferometric measurement of GPS signals proposed by Anderson et al. and can be used to obtain the distance of the GPS antenna from the water surface and get the experimental result of RMS of 12 cm [5]; Larson et al. use GPS-MR technology in Two stations conducted experiments on tidal level monitoring and found that stations with smaller changes in tidal level have higher accuracy [6, 7]; Nakashima and Heki used SNR-based GPS-MR technology to detect sea level change using a single satellite, and get the result of RMS of 27 cm [8]; Löfgren et al. used the wind speed as an indicator of sea surface roughness, SNR analysis performed better than phase delay analysis under rough sea conditions [9]. Taking into account the dramatic changes in the sea surface, Löfgren et al. also used the improved LSP spectrum analysis method to reflect the sea surface tidal level of five GNSS stations in different environments around the world, and found that the improved method When used in stations with large tidal range changes, the results are significantly better than the simple LSP spectrum analysis method [10]; Strandberg et al. use the B-spline method to further enhance the accuracy of tidal level monitoring based on the fusion of multi-mode data. Santamaría-Gómez et al. added a tropospheric correction by laying side antennas, improved Kalman filtering and smoothing algorithm to provide a RMS of 3 cm [12]; Jin et al. based on SNR observations, tri-band combination and code combination BDS-R technology, and used for tidal monitoring [13]; Yu et al. proposed a three-frequency combined observation snow depth detection technology, and use different station environment the experiment is verified [14]; Wang et al. proposed a cGNSS-R epoch measuring algorithm based on single or double difference observation combination, which can effectively weaken the clock error and the ionospheric and tropospheric error to reflect the impact of water surface height [15].

In this paper, the long-term tidal sequence obtained by GNSS-MR technology is analyzed and processed to obtain the average sea surface of the inversion region, which lays a foundation for the subsequent use of the shore-based GNSS station to monitor the regional sea level change and carry out the research on the refined offshore tide model.

2   Basic Theory of Monitoring Tidal Level Changes with GNSS-MR

GNSS multipath effect is regarded as the main error source of high precision positioning. The generation of GNSS multipath is mainly related to the structure and dielectric parameters of the reflective surface. When the GNSS station is located near

the sea surface, the signal received by the GNSS is actually a direct signal and a composite signal reflected by the sea surface.

The GPS receives the signal synthesized by the direct signal and the sea surface reflected signal. The amplitudes of the direct signal and the reflected signal are A_d and A_m respectively. For the measurement type GNSS receiver antenna, the amplitudes of the direct signal and the reflected signal have the following relationship

$$A_d \gg A_m \tag{1}$$

Combined with Fig. 1, among the composite signals A_c captured by the GPS receiver, the direct signal A_d determines the overall trend of the composite signal, that is the overall trend term of the SNR observation, while the reflected signal A_m appears as a local periodic oscillation, which is considered to be mainly due to the low Height angle multipath effect. The SNR observation is the accompanying observation data of the geodetic GPS receiver. The relationship between SNR and signal amplitude is as follows.

$$SNR = A_c^2 = A_d^2 + A_m^2 + 2A_dA_m\cos\theta \tag{2}$$

A_c is the amplitude of the composite signal, and $\cos\theta$ is the cosine of the angle between the direct signal and the reflected signal.

In order to obtain the change information of GPS multipath caused by surface reflection in SNR, the multipath effect needs to be separated from the received SNR observations. Combining Eq. (1), the influence of multipath effect on signal-to-noise ratio is small (mainly at low elevation angle), that is, A_d and A_m are greatly different in value, and low-order polynomial can usually be used to eliminate trend term A_d.
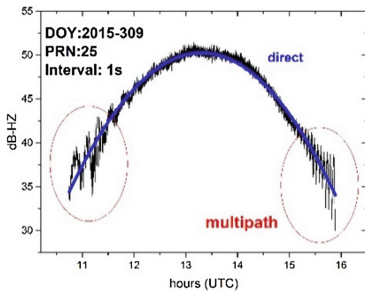

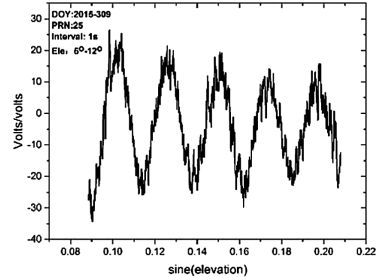**Fig. 1.** SNR variation map of PRN25 GPS satellite.

Fig. 2. Remove the SNR residual sequence of the trend term

Figure 1 shows the SNR variation of the 2015 lakeside GPS station PRN25 satellite with a sampling rate of 1 s. It can be seen from Fig. 1 that the overall trend term of SNR is in parabolic form and can be fitted by quadratic polynomial; the fluctuation of both ends of SNR (GPS satellite rising or falling) is mainly caused by multipath effect at low elevation angle. After the overall trend term in Fig. 1 is removed, the SNR residual sequence caused by multipath effects under low elevation angle conditions can be obtained.

Assume that the amplitude of the SNR residual sequence affected by multipath in Fig. 2 can be expressed as

$$A_m = A\,cos\left(\frac{4\pi h}{\lambda}\,sinE + \phi\right) \tag{3}$$

In Eq. (3), λ is the carrier wavelength, E is the satellite elevation angle, and h is the vertical reflection distance. If $t = sinE$, $f = \frac{2h}{\lambda}$, then Eq. (3) can be simplified to the standard cosine function expression

$$A_m = A\,cos(2\pi ft + \phi) \tag{4}$$

In the Eq. (4), the vertical reflection distance parameter h is included in the frequency f. If the Lomb-Scargle spectrum analysis is performed on the Eq. (4), the frequency f can be obtained, and the antenna phase center to the instantaneous tide level can be obtained vertical distance h.

By performing LSP spectrum analysis on the SNR residual sequence in Fig. 2, the frequency f of the SNR residual sequence can be obtained, and the vertical reflection distance h can be obtained by $f = 2h/\lambda$, and then the change of h is converted into the change of the tidal level. Thereby, real-time monitoring of tidal level changes from SNR observations is achieved.

With the GNSS system providing more than 100 satellite multi-band signals and the number of shore-based CORS stations, the use of GNSS-MR technology to obtain tidal level changes has a high spatial and temporal resolution. The tide gauge station needs to combine GNSS positioning technology and leveling technology to obtain the absolute change of the tide level under the ITRF framework, while the shore-based GNSS station can also measure the vertical deformation of the earth's crust, so GNSS-MR technology has the potential to obtain absolute tide level changes [16–18]. At the same time, GNSS-MR technology can also obtain the tidal wave coefficient, and has the advantages of not contacting with seawater.

3   Basic Principles for Obtaining Sea Level Change Using GNSS-MR Tidal Level Changes

To obtain the daily average sea surface, the long-term trend $a(t - t_0)$ and noise r of sea surface change can be ignored, so Eq. (1) can be expressed as:

$$\zeta(t) = h_0 + \sum_i R_i cos[\sigma_i t - g_i] \tag{5}$$

In Eq. (5), h_0 is the average sea surface to be calculated, the second term is the individual tides, R is the average amplitude in the calculated time range, σ is the angular rate of each tide, and t is the first from the observation. The number of hours counted from zero in day, g indicates the initial phase of the tide in the time range to be calculated, and the average sea surface is calculated based on the data of the actual tide

station $\zeta(t)$. The main principle is to use the difference of the tide-dividing cycle to eliminate by linear combination various tides. In this paper, the Dudson method is used to calculate the daily mean sea surface. This method can theoretically eliminate the influence of the sun and the Taiyue tidal system on the daily average water level.

Long-term tidal level variation sequences can be obtained by using GNSS-MR technology. Since the tidal bit sequences obtained by GNSS-MR technology are not equally spaced samples, the sequence needs to be interpolated and resampled into a new sequence of 1 h sampling interval.

4   Experimental Analysis of GNSS-MR Offshore Sea Level Change

4.1   Experimental Data Source

In order to verify the accuracy of the GNSS-MR technology to obtain the average sea surface, this paper uses the observation data of the GNSS continuous operation tracking station SC02 station (in Fig. 3) located on the shore of the Harbour Harbor in Washington, USA. The SC02 observatory is affiliated with the United States. The PBO network is observed at the edge of the plate in the Earth Scope. The SC02 station is built adjacent to the sea (in Fig. 4). It can receive GPS reflections from the sea surface in a large space. The station has more than ten years of continuous observation data. Figure 3 shows the receiver layout and observation environment of the SC02 station. The receiver used in the SC02 station is the TRIMBLE NETR9 geodetic receiver. The GPS antenna is the Trimble company's choke coil antenna with a fairing (SCIT) (TRM59800.80).

In order to verify the accuracy of GNSS-MR technology to obtain the average sea surface and tidal wave coefficient, this paper makes a comparative analysis using the measured data of the Friday Harbor tide station at 359 meters from the SC02 station. The Friday Harbor Tidal Checkpoint is a continuous operation tide gauge station maintained by the National Oceanic and Atmospheric Administration's Marine Products and Service Center. The tide gauge station was built in 1934 and was equipped with Aquatrak's acoustic test in 1996. The tide gauge can provide tidal level data with a sampling interval of 6 min. Figure 4 shows the relative positional relationship between the tide gauge station and the GNSS station.

Fig. 3. SC02 station observation environment

Fig. 4. SC02 station and tide gauge station relative position

In order to use the GPS data of different time spans for experimental analysis, this paper uses the GPS data of 30 s sampling interval of one month and twelve years to compare with the data of tide gauge station.

4.2   Experimental Analysis of Daily Tide Level Change Using GPS-MR

In Fig. 5, the signal-to-noise ratio data of different frequency bands L1 and L2 of the SC02 station in May 2013 (day 121 to day 151) are used to obtain the daily tide level change and the Dudson method, and with the Friday Harbor tide station. The results obtained by the Dudson method are compared.
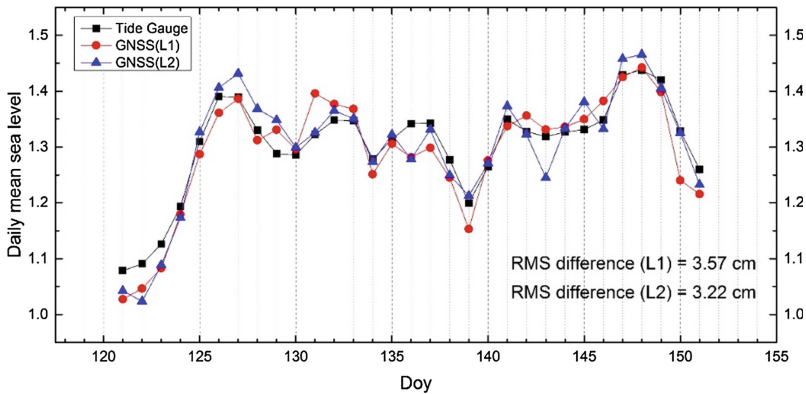

Fig. 5. Comparison of sea level changes between tide station and GNSS-MR in May 2013

In Fig. 5, the horizontal axis represents the annual product day, the vertical axis represents the daily average sea surface relative to the lowest low tide surface, the black point is the daily average sea surface acquired by the Friday Harbor tide station, and the red point is the day obtained by the L1 band of the GPS data of the SC02 station. The average sea surface, the blue point is the daily average sea surface obtained in the L2 band. It can be seen from Fig. 7 that the average daily sea surface obtained in the L1 and L2 bands is in good agreement with the daily average sea surface obtained by the tide station, and the poor average of the results obtained by the L1 band and the tide station is 2.93 cm, the RMS of the difference is 3.57 cm. The poor average of the L2 band acquisition results compared with the tide station results is 2.53 cm, and the difference RMS is 3.22 cm.

4.3   Experimental Analysis of Mean Sea Level Change Based on GNSS-MR Tidal Level Acquisition Area

In order to further verify the effectiveness of GNSS-MR technology to monitor regional sea level change, the monthly average sea surface from 2005 to 2017 was obtained by using the signal-to-noise ratio of L1 frequency band according to the flow of Fig. 4,

and compared with the results of tide gauge station. (in Figs. 6 and 7). In order to obtain the average sea level change rate, the monthly average sea surface sequence is generally fitted by the least squares method, and the slope of the fitted straight line is the average sea level change rate. Figure 6 shows the monthly average sea surface change of the GNSS-MR from SC02 station from 2005 to 2017, and Fig. 7 shows the monthly mean sea level change of the Friday Harbor tide station.
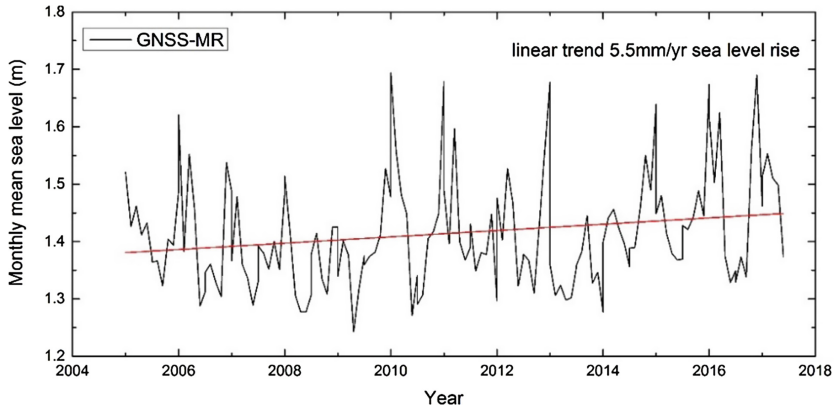

Fig. 6. Monthly mean sea level change of GNSS-MR from 2005 to 2017
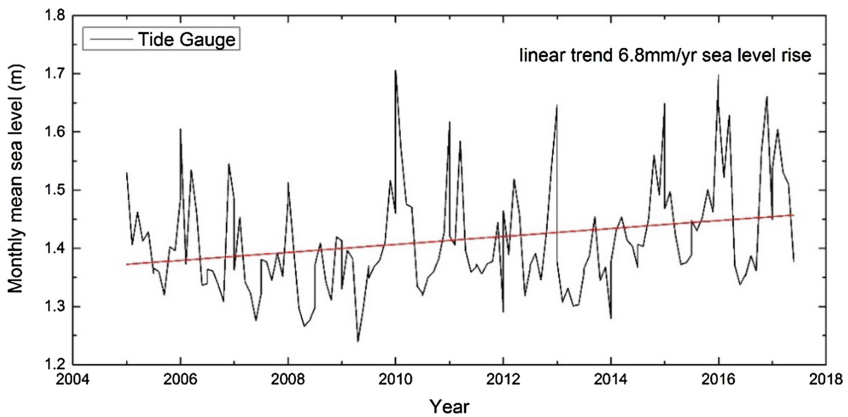

Fig. 7. Comparison of monthly mean sea level changes at tide stations from 2005 to 2017

The black lines in Figs. 6 and 7 are the monthly mean sea surface sequences obtained by the SC02 station and the Friday Harbor station respectively, and the red line is the straight line fitted by the least squares method. The monthly mean sea surface change rate obtained by the SC02 station is 5.5 mm/yr, and the monthly average sea surface change rate obtained by the Friday Harbor station is 6.8 mm/yr. From the

experimental results of Figs. 6 and 7, it can be seen that the GNSS-MR technology agrees well with the monthly average sea surface change rate obtained by the tide gauge station, and verifies the feasibility of the GNSS-MR technique to obtain the regional average sea surface change rate.

5   Conclusion

Based on the existing research results, and the basic theory of daily mean sea surface acquisition, this paper gives the method of GNSS-MR technology to obtain the average sea surface change. The accuracy of GNSS-MR technique for obtaining average sea surface change is analyzed by an example. The following conclusions are drawn:

(1) GNSS-MR technology can effectively obtain long time series of tidal level, which is in good agreement with the results of tide gauge station, so GNSS-MR technology provides an effective supplementary means for obtaining tidal level changes.

(2) The average sea surface obtained by GNSS-MR technology obtained from the average sea surface and the tide gauge station is in good agreement with the overall trend. The long-period monthly average sea surface change rate obtained by GNSS-MR was solved by least squares method, and compared with the monthly mean sea surface change rate obtained from the Friday Harbor tide station at 359 meters, the GNSS-MR technique was used to obtain the regional mean sea surface change. The effectiveness of the rate. To lay the foundation for the GNSS-MR technology to obtain the absolute change of regional average sea surface.

GNSS-MR technology has the advantages of high time resolution, no contact with seawater, and multi-purpose use in obtaining tidal level and regional average sea surface. At the same time, the high-precision acquisition of regional sea level changes complements the satellite altimetry for GNSS-MR technology and lays a foundation for the refinement of offshore tide models.

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