Tide Height Inversion and Accuracy Analysis Based on GNSS-MR Technology

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Abstract. The tide height of offshore waters is an indispensable marine geographic information data for marine traffic, offshore environmental management, and marine disaster warning and forecasting. Recently years, with the advantages of low power consumption and low cost, the Global Navigation Satellite System Multipath Reflection (GNSS-MR) technology has become an emerging technical method of tide height measurement. In this article, the observation files of SC02 station in 2018 in Washington state of United States is used to retrieve the distance in vertical direction from antenna phase center to sea surface by using the change of signal-to-noise ratio (SNR) caused by the multipath effect of navigation satellite signal. Afterwards, the elevation based on International Terrestrial Reference Frame (ITRF) is converted to the elevation based on the Mean Lower Low Water (MLLW). And then the tide height of each inversion time relative to MLLW is obtained. Finally, the retrieved tide height is compared and analyzed with the tide height offered by the tide gauge station named FRIDAY HARBOR. The results show that the mean error of the two is about −12 cm, the root mean square error is about 15 cm, and the correlation coefficient is about 0.98. Overall, the retrieved tide height agrees well with the measured tide height. Hence, the tide height retrieved by GNSS-MR technology can make up for the lack of ocean observation data in the coastal waters and plays an important role in marine scientific research.

Keywords: Tide height · GNSS-MR · SNR · MLLW

1 Introduction

The Global Navigation Satellite System (GNSS) not only provides navigation and positioning, speed measurement, timing and other information for users of spatial information, but also provides L-band microwave signals that can be used for a long time, which contribute to the creation of the GNSS-MR technology [1]. The tide height in the coastal waters is an important marine geographic information data, which is of great significance to marine scientific research.

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At present, the tide height is mainly obtained by means of tide gauge and satellite altimeter. Recently years, with the continuous progress of GNSS-MR technology, it has become possible to measure tide height by GNSS-MR technology. In 2014, Lofgren et al. extracted the observation files of five GPS stations distributed in the northern and southern hemispheres to analyze the variations of sea level with time series, and the correlation coefficients were all between 0.89–0.99, which has a good consistency in general [2]. In the same year, Lofgren and Haas proposed to use SNR and carrier phase to retrieve the tide height respectively, and the results showed good correlation [3]. In 2015, Roussel et al. proposed a new mean which is based on the least square method (LSM) that combined the SNR of GPS and GLONASS system to retrieve the tide height. The correlation coefficient was significantly improved [4]. In 2016, Zhang et al. selected SC02 station to monitor the change of sea level, and compared it with the tide height of tide gauge. Results showed that the correlation coefficient between them was better than 0.98 [5]. In the same year, Strandberg et al. proposed to use L1 and L2 signals of GPS and GLONASS for inversion, proving that both signals can be used for tide height inversion [6]. In 2018, Wang et al. proposed a method to determine the sea area azimuth angles and elevation angles of the station, and conducted analysis on stations of PBAY, SC02 and BRST respectively [7]. In 2019, Puente and Valdés used multi-system and multi-frequency to invert the tide height in the coast of Spain, and analyzed the advantages and disadvantages of this method [8]. In the same year, Fade Chen used the SNR data of the BDS, GPS, and GLONASS of the MAYG station to generate the initial tide waveform, combined with wavelet denoising to retrieve the tide height, and the correlation coefficient was increased to 0.95 [9].

In this paper, the method and theory of GNSS-MR technology to invert the tide height is systematically introduces. The observation data of SC02 station in 2018 is selected for inversion of tide height, and compared with the tide height of FRIDAY HARBOR which is 359 m away from SC02 station, then accuracy analysis is performed. The results show that the tide height retrieved by GNSS-MR technology can be used to make up for the shortage of ocean observation data in the coastal area.

2 Theoretical of Tide Height Inversion by GNSS-MR

2.1 Fundamental

In actual, the inversion of tide height by GNSS-MR technology is to retrieve the distance in vertical direction from the antenna phase center to sea level by using the change of SNR. As we all know, the MLLW is used as the chart depth reference surface in the United States. Afterwards, the elevation based on ITRF is converted to the elevation based on the MLLW. And then the tide height of each inversion time relative to MLLW is obtained. Figure 1 shows the diagram of tide height inverted by

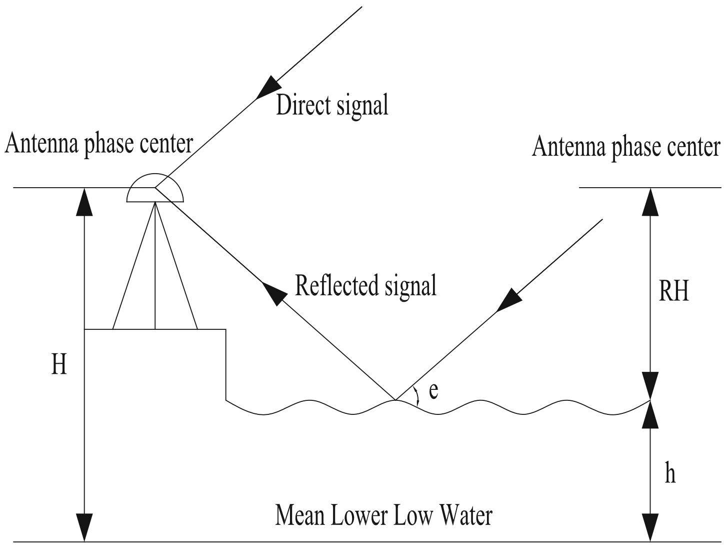

Fig. 1. Diagram of tide height inverted by GNSS-MR

GNSS-MR Technology. Where H is the height from the MLLW to the antenna phase center, RH is the vertical reflection distance from the sea surface to the antenna phase center, h is the measured tide height from the MLLW to the sea surface, and e represents the satellite elevation angle.

Figure 1 shows the SNR change of the PRN10 at SC02 station of doy335 in 2018, and the overall SNR trend of the satellite in the ascending and descending phases is shown. In the short time of satellite ascent and descent, there is a tendency that the SNR amplitude is significantly larger. Figure 2(a) extracts the original SNR data of PRN10 and obtains the direct signal through low-order polynomial fitting [10, 16]. The blue line represents the change of original SNR with time series, and the orange line reflects the overall trend of SNR after low-order polynomial fitting. Figure 2(b) is the SNR residual (δSNR) caused by multipath effect in the SNR after removing the overall trend. The blue line reflects the change of δSNR, and the orange line reflects the change of the satellite elevation angle during this period. The figure clearly shows that the variations of δSNR is closely related to the satellite elevation angle. At high elevation angles, δSNR is about ±2 dB-Hz; while at low elevation angles, δSNR amplitude is obviously larger, reaching ±5 dB-Hz. It indicates that δSNR is affected by multipath effect at low elevation angles, which provides a basis for using multipath effect to invert tide height.

In Fig. 1, the path delay caused by the multipath effect is:

$$D = 2RH \sin e \tag{2.1}$$

Where D is the path delay caused by the reflected signal and the direct signal during the propagation of the satellite signal.

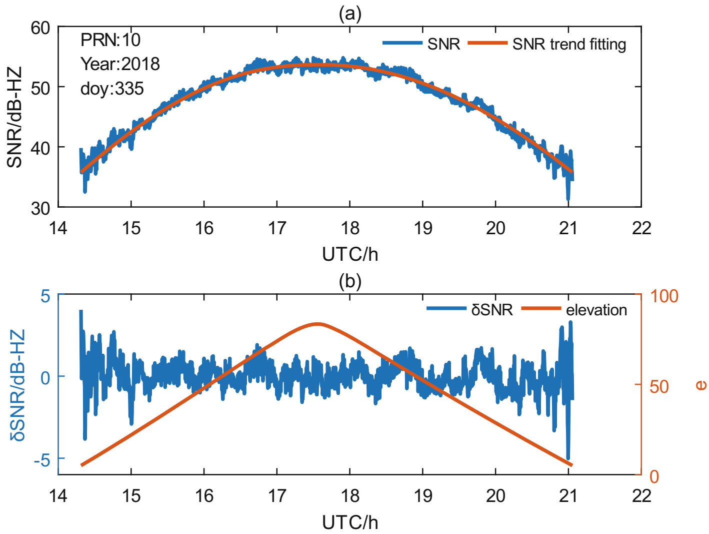

Fig. 2. SNR variations of PRN10

In Fig. 2, the phase difference of δSNR affected by multipath is [11]:

$$\varphi_i = \frac{2\pi D}{\lambda} \tag{2.2}$$

Where φ is the phase difference between the reflected signal and the direct signal, λ is the length of the band, and the signal length of the L1 band is taken as $\lambda_1 = 19.03$ cm.

Lomb-Scargle (L-S) spectral analysis is performed on the δSNR in Fig. 2, and the frequency of the δSNR is [12, 13]:

$$\omega_\varphi = 2\pi f = \frac{d\varphi_i}{d\ sin\ e} \tag{2.3}$$

From the formulas (2.1), (2.2) and (2.3), the vertical reflection distance from the sea surface to the antenna phase center is [14, 15]:

$$RH = \frac{\lambda f}{2} \tag{2.4}$$

According to Fig. 1, the tide height retrieved by GNSS-MR is:

$$GNSSMR_h = H - RH \tag{2.5}$$

Where $GNSSMR_h$ is the tide height retrieved by GNSS-MR technology.

2.2 Accuracy Analysis

In this paper, the observation data with an ebb period and a year of SC02 station in 2018 are taken as examples to invert tide height and perform accuracy analysis. The selected accuracy indicators are mean error (*MEAN*), root mean square error (*RMSE*), and correlation coefficient (*COEF*). The calculation formulas are as follows:

$$MEAN = \frac{1}{n}\sum\nolimits_{i=1}^{n} (GNSSMR_h - TG_h) \quad (2.6)$$

$$RMSE = \sqrt{\frac{1}{n}\sum\nolimits_{i=1}^{n} (GNSSMR_h - TG_h)^2} \quad (2.7)$$

Where TG_h is the tide height measured by the tide gauge.

3 An Example Analysis of Tide Height Inverted by GNSS-MR

3.1 Station Environment

In order to ensure that the satellite signal received in the experiments are reflected from sea level, the elevation angles range is selected as 5°–12° and the azimuth angles range is selected as 90°–150° when using the L1 signal of the satellite for tide height inversion.

When using the observation files of SC02 station of the GPS Continuous Operation Reference Station (CORS) located in Washington state, USA to retrieve the tide height, it involves the elevation conversion between datum of ITRF08 and MLLW. The parameters of SC02 station are listed in Table 1:

Table 1. Parameters of SC02 in 2018

Station	SC02
Latitude (°)	48.54619494
Longitude (°)	−123.00761033
Height (m)	−15.0345
Region	Contiguous United States
Reference frame	ITRF08
Reference epoch	2004.4973
Tide gauge	FRIDAY HARBOR
Distance to tide gauge (m)	359
Antenna type	TRM59800.80
H (m)	6.603
TCR (m)	0.1020

Through the above parameters, the elevation of the antenna phase center based on MLLW is obtained. The schematic is shown in Fig. 3. Then the tide height retrieved by GNSS-MR technology is calculated by formula (2.5). And it is compared with the measured tide height of FRIDAY HARBOR provided by the National Oceanic and Atmospheric Administration (NOAA) every 6 min.

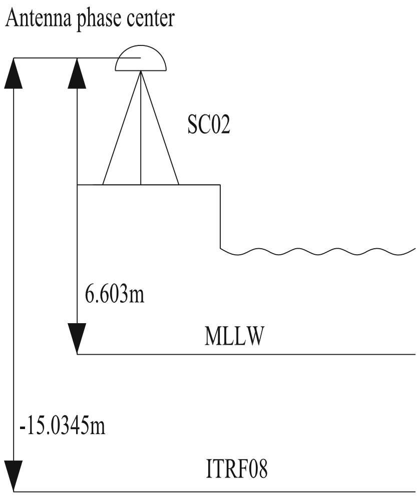

Fig. 3. The elevation conversion between datum of ITRF08 and MLLW

3.2 Analysis of the Inversion Results of an Ebb Tide Period

In order to analyze the periodicity of tide height inverted by GNSS-MR multi-system, SNR in L1 band provided by GPS and GLONASS at SC02 station during the period of doy335–350 in 2018 is extracted for tide height inversion. Table 2 takes the observation data of doy335 as an example, and gives the comparison results of the tide height retrieved by GPS and the tide height measured by tide gauge. It is found that the deviations between the two are −0.2–0.2 m, which has a good consistency. And T represents the time length of L-S spectrum analysis. Mean UTC represents the average time during the spectrum analysis period.

Table 2. Comparison of GNSS-MR and tide gauge

PRN	T/min	Mean UTC/h	RH/m	$GNSSMR_h$/m	TG_h/m	Deviations/m
01	23	4.88	5.41	1.295	1.415	−0.120
10	19	20.90	3.89	2.815	2.655	0.160
13	23	13.38	5.95	0.755	0.729	0.026
20	19	19.74	4.00	2.705	2.675	0.030
24	26	16.56	4.92	1.785	1.707	0.078
27	22	1.00	5.27	1.435	1.464	−0.029
28	20	8.69	5.25	1.460	1.340	0.120
07	18	6.08	5.25	1.455	1.507	−0.052
08	20	1.47	5.32	1.385	1.382	0.003
15	20	13.52	5.93	0.775	0.753	0.022
16	18	22.35	4.46	2.250	2.306	−0.056
23	16	3.38	5.28	1.425	1.285	0.140
26	20	21.56	4.25	2.450	2.528	−0.078
30	17	7.30	5.29	1.415	1.504	−0.089

Figure 4 shows the δSNR variations and L-S spectral analysis results of the PRN01 satellite after linearization. In Fig. 4(a), the abscissa is the sine of the elevation angles and the ordinate is δSNR. It is found that the amplitude becomes smaller and smaller with the increase of the elevation angles. In Fig. 4(b), the abscissa is the vertical reflection distance and the ordinate is the L-S spectral amplitude of δSNR. And the vertical reflection distance corresponding to the peak of the L-S spectral amplitude is the height from the antenna phase center to the instantaneous sea level, so the vertical reflection distance calculated by the PRN01 satellite at mean UTC of 4.88 h is 5.41 m.

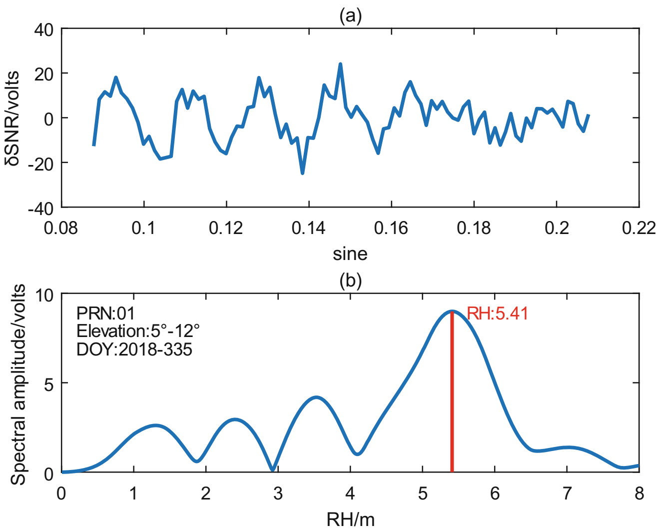

Fig. 4. SNR residual sequence and L-S spectral analysis

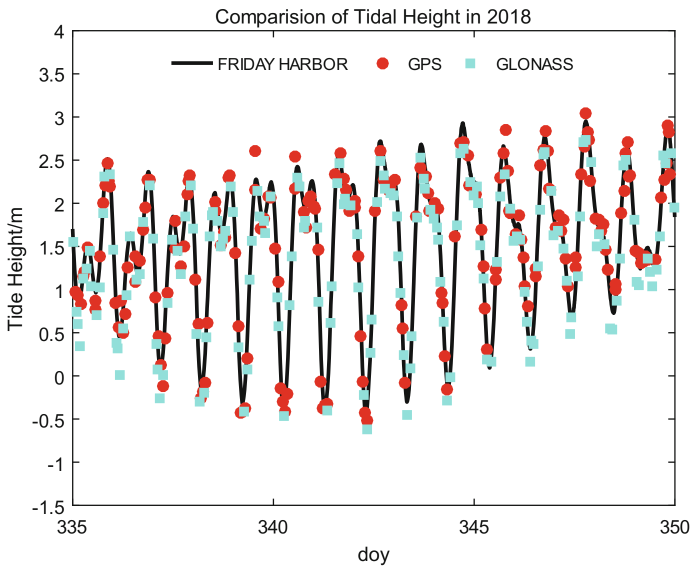

Fig. 5. Comparison of tide height between GNSS-MR and tide gauge

Figure 5 shows the comparison of tide height between GNSS-MR and FRIDAY HARBOR. In the figure, the black line represents the measured tide height of FRIDAY HARBOR, the red dots represent the 208 instantaneous tide height retrieved by the GPS satellite, and the cyan dots represent the 181 instantaneous tide height retrieved by the GLONASS satellite. It can be seen from the figure that there exists tide height retrieved by GNSS-MR at both the tide peaks and the tide valleys, indicating that this method can not only reflects the rising and falling tide trend of a day, but also reflects the variations trend of tide height during the ebb tide period. Overall, the retrieved tide height agrees well with the measured tide height.

Table 3. Inversion of tide height at SC02 station in 2018 of doy335–350 by GPS, GLONASS and GPS+GLONASS

Constellation	MEAN/m	RMSE/m	COEF
GPS	−0.042	0.154	0.984
GLONASS	−0.157	0.129	0.987
GPS+GLONASS	−0.096	0.154	0.983

Table 3 shows the comparison statistics of tide height retrieved by GPS, GLONASS and GPS+GLONASS. Results show that the MEAN of all three are negative values, and the MEAN of GPS is the smallest, which is −0.042 m. The RMSE of GLONASS is the smallest, which is 0.129 m, and the COEF is the largest, which is 0.987. Although the COEF of GPS+GLONASS dual satellite system is slightly lower than that of single satellite system, the retrieved tide height still has good consistency. With the increase of the number of retrieved instantaneous tide height, its spatial-temporal resolution is also significantly improved, which verifies the feasibility of multi-system inversion of tide height.

Figure 6 shows the correlation analysis and error deviations of tide height between GNSS-MR and FRIDAY HARBOR tide gauge. Figure 6(a)–(c) are the correlation analysis diagrams between the tide height retrieved by GPS, GLONASS and GPS +GLONASS and the tide height measured by tide gauge. It can be seen from the figure that the tide height retrieved by GPS and GPS+GLONASS is evenly distributed on both sides of the anastomosis line, while most of the tide height retrieved by GLONASS is below the anastomosis line, which makes the retrieved tide height less than the measured tide height. It may be caused by some uncertain factors of GLONASS, which needs further discovery and research. Figure 6(d)–(f) intuitively reflect the deviations between the tide height retrieved by GPS, GLONASS and GPS+GLONASS and the tide height measured by tide gauge. Most of the tide height deviations retrieved by GPS are concentrated in −0.3–0.2 m, and most of the tide height deviations retrieved by GLONASS are concentrated in −0.4–0.1 m, indicating that the tide height retrieved by GNSS-MR has a high accuracy.

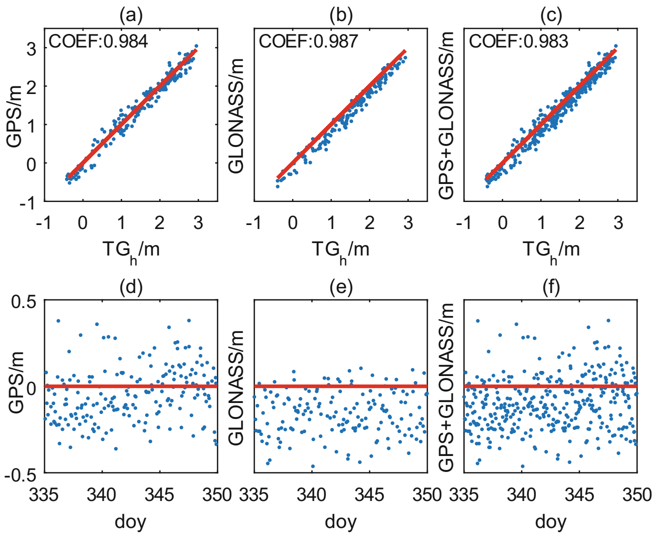

Fig. 6. Correlation analysis and error deviations of tide height between GNSS-MR and tide gauge

3.3 Analysis of the Inversion Results of a Year in 2018

In order to analyze the continuity of tide height inverted by GNSS-MR multi-system, SNR in L1 band provided by GPS and GLONASS at SC02 station in 2018 is extracted for tide height inversion. It should be noted that the long-period tide height inversion value covers the vertical movement of the GPS station, and the vertical displacement of the GPS station of SC02 station studied in this paper is small, so it can be ignored.

Table 4 shows the comparison statistics of tide height retrieved by GPS, GLONASS and GPS+GLONASS in 2018. Results show that the MEAN of all three are negative values, and the MEAN of GPS is −0.074 m, and that of GLONASS is −0.165 m. There is a certain deviation between the two systems. The RMSE of GLONASS is the smallest, which is 0.124 m, and the COEF is the largest, which is 0.987. Although the COEF of GPS+GLONASS dual system is slightly lower than that of single system, the retrieved tide height still has good consistency. With the increase of the number of retrieved instantaneous tide height, its spatial-temporal resolution is also significantly improved, indicating that the tide height retrieved by GNSS-MR multi-system can reflect the continuous change of a year, and generally can be used to describe the tide height change of a long time series.

Table 4. Inversion of tide height at SC02 station in 2018 by GPS, GLONASS and GPS +GLONASS

Constellation	MEAN/m	RMSE/m	COEF
GPS	−0.074	0.163	0.976
GLONASS	−0.165	0.124	0.987
GPS+GLONASS	−0.116	0.152	0.980

Figure 7 shows the correlation analysis and error deviations of tide height retrieved by GPS+GLONASS and the tide height measured by FRIDAY HARBOR tide gauge. Figure 7(a) are the correlation analysis diagrams of the two. The MEAN is −0.116 m, the RMSE is 0.152 m, and the COEF is 0.980, which indicates that the tide height retrieved by GNSS-MR can show the continuity of the tide height with time series. Figure 7(b) shows the variations of the errors between the two with day of year (doy). As shown in the figure, most of the errors are concentrated in −0.4–0.2 m, which is affected by GLONASS, leading to the overall value to be negative. At present, this part of errors may be caused by two reasons. On the one hand, the instantaneous tide height retrieved by GNSS-MR deviates from the measured tide height by tide gauge due to the wave fluctuations on the sea level. On the other hand, the GNSS observation stations and tide gauge are not located at the same place, which inevitably causes errors in the conversion process of elevation datum.

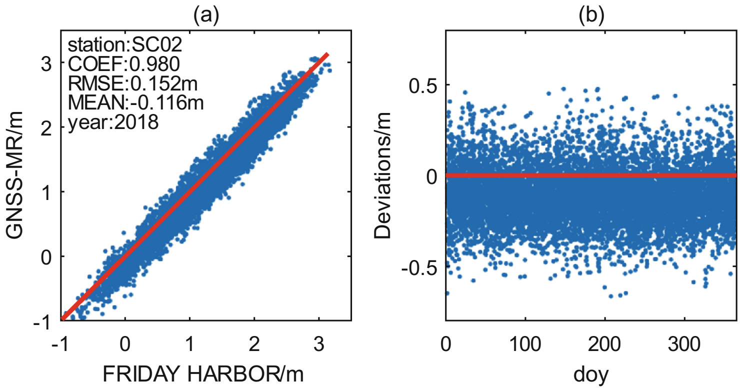

Fig. 7. Correlation analysis and error deviations of tide height between GNSS-MR and tide gauge

4 Conclusions

In this paper, the observation files of SC02 station in 2018 are taken as examples to invert the tide height and analyze the accuracy. The conclusions are as follows:

(1) From the data analysis of 2018, the instantaneous tide height retrieved by GNSS-MR technology based on SNR has obvious periodicity and continuity, which can show the dynamic change of tide height with time series. Compared with the measured tide height by tide gauge, it has good consistency in general. As a new remote sensing method, the retrieved tide height by GNSS-MR can be used to make up for the lack of ocean observation data in the coastal waters, which plays an important role in marine scientific research.

(2) Combining GPS and GLONASS dual system to perform tide height inversion, the spatial-temporal resolution is significantly improved. The MEAN between the two is about −12 cm, the RMSE is about 15 cm, and the COEF is about 0.98. In the future, the effects of integrating the four major systems of GPS, GLONASS, Galileo and BDS on the accuracy of the tide height inversion will be further discussed.

(3) At present, the GNSS-MR technology has preliminarily realized the function of the tide gauge. The next step will continue to study how to reduce the impact of wave fluctuations on the tide height and the errors caused by the no co-located between GNSS observation stations and the tide gauge.

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