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Research on Shore-based Water Height Measurement Method Based on Satellite Navigation Reflected Signal-to-noise Ratio

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Abstract

Sea level rise due to global warming will have a major impact on human society, especially for the population living on coastal areas and islands. It is crucial to monitor sea level and increase understanding of the local hydrodynamic and meteorological responses to global sea level rise. In this paper, the geometrical relationship and model of shore-based water surface height measurement based on the signal-to-noise ratio (SNR) of satellite navigation reflection signals are constructed. The characteristics of detrended signal-to-noise ratio are analyzed. The function fitting method and Lomb-Scargle Periodograms (LSP) method are analyzed. The GNSS receiver of the coastal IGS station uses the analyzed SNR altimetry method to monitor the global coastal sea level.

Keywords

Sea level, GNSS-R, Signal-to-noise ratio, Altimetry method.

1. Introduction

Global Navigation Satellite Systems Reflectometry (GNSS-R) is a new type of remote sensing method with low cost, low power consumption, and relatively high spatial and temporal resolution [1]. It uses the reflected signals of navigation satellites to remotely sense sea or land surfaces and obtains the information of the reflecting surface by reflecting the signals on the sea surface, land and vegetation. GNSS-R is widely used, and the snow depth, sea breeze, soil moisture and so on [2-7]. The methods of sea level height measurement are endless and the application of GNSS-R sea level height measurement method is more and more widely used. In addition, the absolute sea level measurement including GNSS measurement may also be very important for the calibration of satellite altimeter. By combining the altimeter record with the tide gauge record, the instrument deviation in the altimeter data can be corrected. Compared with traditional tide instruments, the advantage of using reflected GNSS signals for sea surface remote sensing can be used for measuring the absolute sea level.

At present, domestic and foreign GNSS-R altimetry platforms include spaceborne, airborne, and shore-based methods. Sea-level height measurement techniques mainly include carrier phase method, code phase method, and the recently popular SNR method. The carrier phase method and the code phase method are based on the measurement method of phase difference. These two measuring methods have the same principle and both use the height relationship between the path delay of the reflected signal and the sea level when the sea level changes. The carrier phase method decays the energy of the reflected signal after being reflected by the sea level. The height measurement method of the code phase makes the measurement accuracy poor due to the large width of the C / A chip. The SNR-based altitude measurement method is a relatively popular method in recent years. However, the SNR-based measurement method is critical to the selection of satellite altitude angle. Improper selection of satellite altitude angle will be an important source of altitude measurement error. This paper constructs the geometrical relationship and model of shore-based water surface height

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measurement based on the signal-to-noise ratio of satellite navigation reflection signals. Then the characteristics of signal-to-noise ratio (SNR) are analyzed, and the function fitting method and LSP method are also presented, respectively. The methods can be used in monitoring the global coastal sea level using GNSS receivers of global coastal IGS stations.

2. GNSS-R SNR altimetry technology principle

2.1 Geometric relationship of height measurement

Figure 1 shows the geometric relationship of sea level height measurement. Here, we assume the surface of the earth is not curved. It can be seen from the above figure that the reflected signal has taken a part longer than the direct signal. The extra distance is the additional path delay. Therefore, the additional path delay of the GPS signal relative to the direct signal is [2]:

$$\rho_E = \rho_I + \rho_R = \rho_I + \rho_R' \tag{1-1}$$

The mathematical relationship between them is:

$$\rho_I + \rho_R' = 2h_{R-s} sin\theta \tag{1-2}$$

h_{R-S}refers to the height of the antenna relative to sea level, θ is the elevation angle of the observed satellite.

Then the sea level is:

$$h_s = h_R - h_{R-s} = h_R - \frac{\rho_E}{2\sin\theta} \tag{1-3}$$

$h_R$refers to the height of the antenna receiver, the reference plane is the earth, and θ is the satellite elevation angle. $h_R$refers to the height of the antenna receiver, andθ the satellite elevation angle.

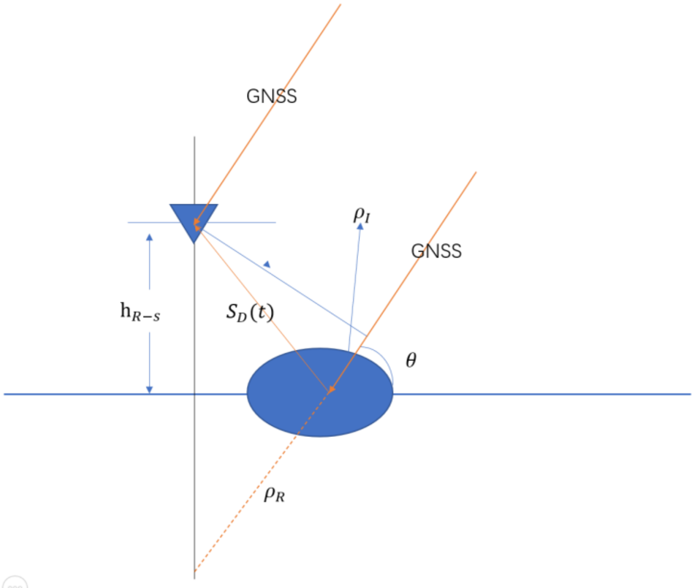

Figure 1 GNSS-R sea surface height measurement geometric relationship

2.2 Height measurement model of SNR

The height measurement model of the signal-to-noise ratio is shown in Figure 2. Here, the vertical point of the reflected signal made by the A point and refers to the corresponding point of the B antenna receiver relative to sea level. Point C is the antenna receiver. D is the vertical point from the antenna to the sea surface, O is the reflection point, $\theta_{el}^{s}$is the angle between the satellite signal and the sea surface, Δx is the horizontal distance from the receiver to the reflection point, h is the height of the receiver from the sea surface CD, h changes Reflecting the change in sea level height, the path delay is.

$$\overline{\Delta d} = \overline{AB} = \overline{AO} + \overline{OB} = \overline{AO} + \overline{OC}$$

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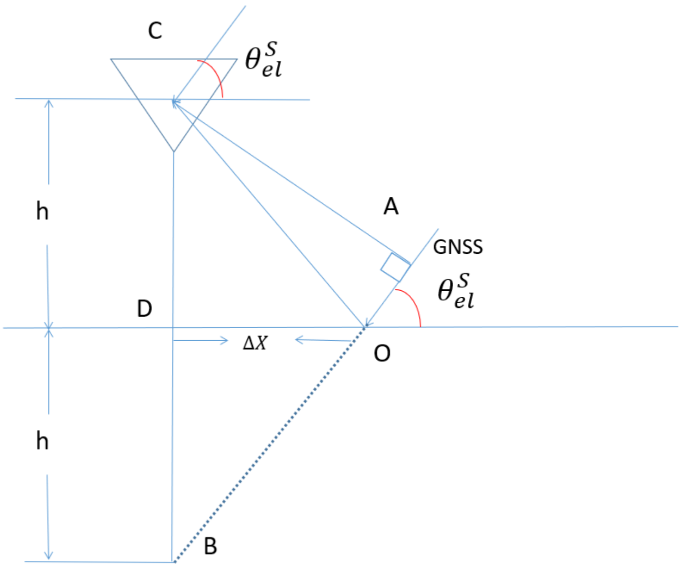

Figure 2 Schematic diagram of SNR sea surface altimetry principle

In the Δ ABC triangle, the reflected signal takes more paths than the direct signal, $\Delta d = AB = AO + OB = AO + OC$, Satellite elevation angle is θ_{el}^{s},
The satellite signal frequency is f_{L1}, and h is the height from the receiver antenna phase center to the sea surface. Therefore, h is regarded as the sea surface height [3].

$$\cos(\frac{\pi}{2} - \theta_{el}^{s}) = \frac{AB}{BC} = \frac{\Delta d}{2h} \tag{1-4}$$

$$\Delta d = 2h\cos(\frac{\pi}{2} - \theta_{el}^{s}) = 2h\sin(\theta_{el}^{s}) \tag{1-5}$$

$$h = \frac{\Delta d}{2\sin(\theta_{el}^{s})} \tag{1-6}$$

The carrier phase of the reflected signal is:

$$\phi_{R}^{s} = \frac{\Delta d}{\lambda} * 2\pi = \frac{\Delta d}{\frac{c}{f_{L1}}} * 2\pi = \frac{\Delta d * f_{L1} * 2\pi}{c} = \frac{2h\sin(\theta_{el}^{s}) * f_{L1} * 2\pi}{c} = \frac{4\pi f_{L1} h}{c} * \sin(\theta_{el}^{s}) \tag{1-7}$$

The total signal (including direct signal and reflected signal) received by the receiver antenna of the s satellite is:

$$\begin{aligned} S_G(n) &= \sum_{s\in\{S\}} S_D^s(n) + \sum_{s\in\{S\}} S_R^s(n) \\ &= \sum_{s\in\{S\}} A_D^s \cos(2\pi f_{L1}{}^{s} nT_c + \phi_D^s) CA^s((n+\tau_D^s)T_c) \\ &+ A_R^s \cos(2\pi f_{L1}{}^{s} nT_c + \phi_R^s) CA^s((n+\tau_D^s)T_c) \end{aligned} \tag{1-8}$$

It can be converted into a composite signal:

$$S_G^s(n) = A_G^s CA^s((n+\tau_D^s)T_c)\cos(X - \phi_G^s) + \omega(n) \tag{1-9}$$

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$$X = 2\pi f_{L1}{}^{s} nT_c + \phi_D^s$$
$$\phi_G^s = \arctan\left(\frac{A_R^s \sin(\phi_R^s)}{A_D^s + A_R^s \cos(\phi_R^s)}\right)$$
$$A_G^s = \sqrt{(A_D^s)^2 + (A_R^s)^2 + 2A_D^s A_R^s \cos(\phi_R^s)} \quad (1\text{-}10)$$

A_G^s is the amplitude of the synthesized signal, φ_G^s is the phase angle of the synthesized signal; $\emptyset_D^s$ is the navigation message information; A_D^s is the pseudo-random code; A_R^s is the period of the pseudo-random code; F is the amplitude of the direct signal, G is the amplitude of the reflected signal; $\emptyset_D^s$ Is the carrier phase of the direct signal, $\emptyset_R^s$ is the carrier phase of the reflected signal; $\omega(n)$ represents Gaussian white noise with a variance. Assuming that the received signal noise is Gaussian white noise, and the SNR is[4]:

$$SNR = (A_D^s)^2 + (A_R^s)^2 + 2A_D^s A_R^s \cos(\phi_R^s) \quad (1\text{-}11)$$

The square of the amplitude of the direct signal and the amplitude of the reflected signal will increase the SNR [5]. This requires the SNR minus the n-order polynomial to detrend (n is generally 2). The reflected signal causes the SNR to have small amplitude high-frequency oscillation changes [6].

3. SNR feature extraction

Removal of $(A_D^s)^2 + (A_R^s)^2$ [7] from equation (1-11) removes the second-order polynomial, and the trended signal-to-noise ratio &SNR is removed:

$$\delta SNR = 2A_D^s A_R^s \cos(\phi_R^s) \quad (1\text{-}12)$$

$$\delta SNR(\sin(\theta_{el}^s)) = 2A_D^s A_R^s \cos(\phi_R^s) = 2A_D^s A_R^s \cos\left(\frac{4\pi f_{L1} h}{c}\sin(\theta_{el}^s)\right) \quad (1\text{-}13)$$

$sin\,\theta_{el}^S$ is an independent variable [8].

The SNR value is a scaled version of the signal amplitude (assuming a constant noise level), which is derived from the carrier tracking loop of the GNSS receiver. Figure 3 is the SNR graph of the 26th satellite with elevation angle on January 4, 2016.

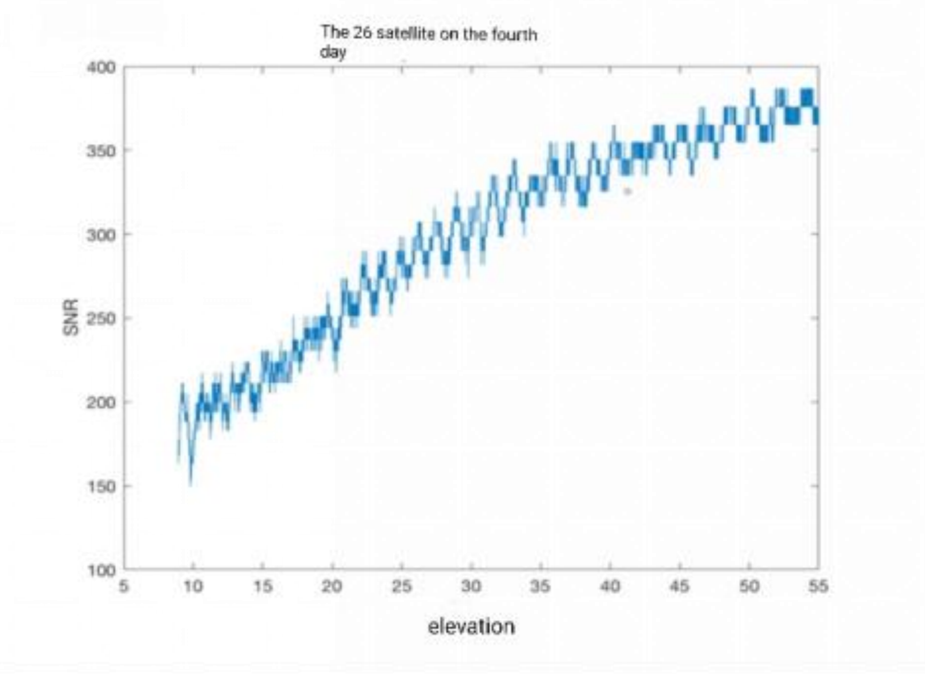

Figure 3 The un-trended elevation SNR of the PRN26 on the fourth day of 2016

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Figure 4 shows the de-trending elevation SNR graph when the elevation angle between 5-10 degrees.

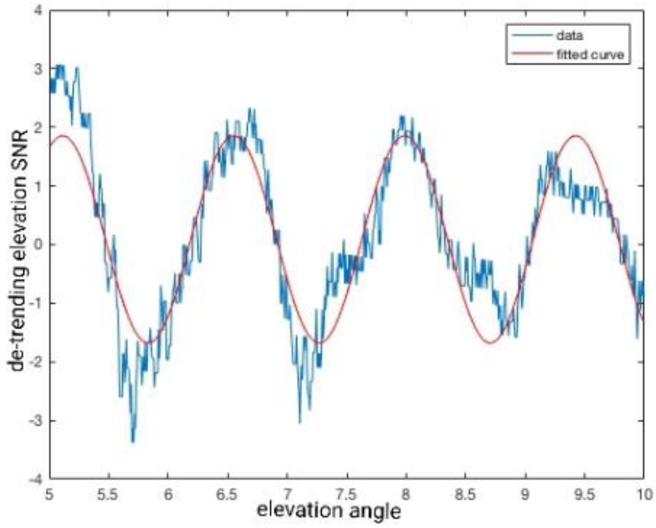

Figure 4 Detrended elevation SNR image

It can be seen from the figure that this is the detrended elevation-SNR graph after the elevation angle is within 5º-10º. This curve is very close to the sinusoidal curve. According to the relationship between the frequency of the sinusoidal curve and the signal propagation speed, the path delay can be obtained. Equation 1-6 can be used to obtain the height of sea level.

4. Altimetry method

4.1 Function fitting method

The detrended SNR is similar to a sine function. We use the sine fitting method to find the SNR vibration frequency according to the period of the sine function, mainly using the formula $y = A\sin(\omega t + \varphi)$. The angular frequency can be calculated, and this formula is used to obtain the oscillation frequency [9-10]. Figure 5 shows the result of an example of the fitting method. This is an elevation SNR sine fitting image, R-square reaches 0.8192, R-square is the coefficient of determination, the maximum value is 1, the greater the better the fit. The angular frequency is w = (5.04, 5.116), and according to the formula f = ω / (2π), the sea level height expression h = 0.095 * f = 3.3989m. The sea level height is obtained by sinusoidal fitting, and the height of the GPS antenna receiver has been subtracted, and the result is the sea level height changes.

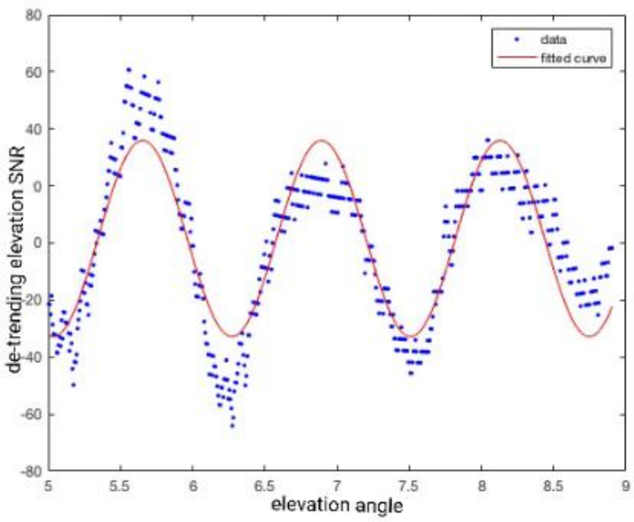

Figure 5 The function fitting method

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4.2 LSP method

The sampling of satellite signals is affected by many factors, resulting in a sampling period that is not completely uniform [11]. The LSP method can extract the non-uniform periodic signal in non-uniform sampling and can also suppress the generation of false signals to a certain extent. For the power spectrum analysis of non-uniformly sampled time series, we use the Lomb-Scargle method for the height retrieval [12]. Figure 6 is the LSP spectrum conversion diagram. We use the reflected signal of the PRN12 on January 3, 2016. The satellite altitude angle is selected from 5º-10º elevation. This transform the LSP spectrum can be used to find the sea level height. The height of the receiver from the sea level is 4.5566m.

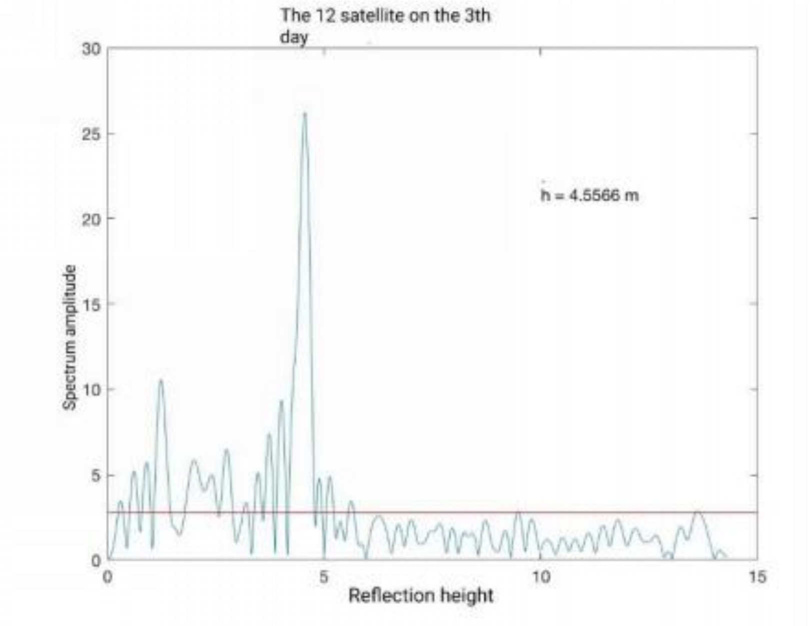

Figure 6 The LSP spectrum

Figure 7 shows the comparison of the sea level height measured by the tide gauge and the sea level height measured by the receiver. It can be seen from Figure7 that the red dots represent the sea level height measured by the tide gauge, the blue line represents the sea level height measured by the SNR method, and the red uniformity is scattered around the blue, which has a strong correlation.

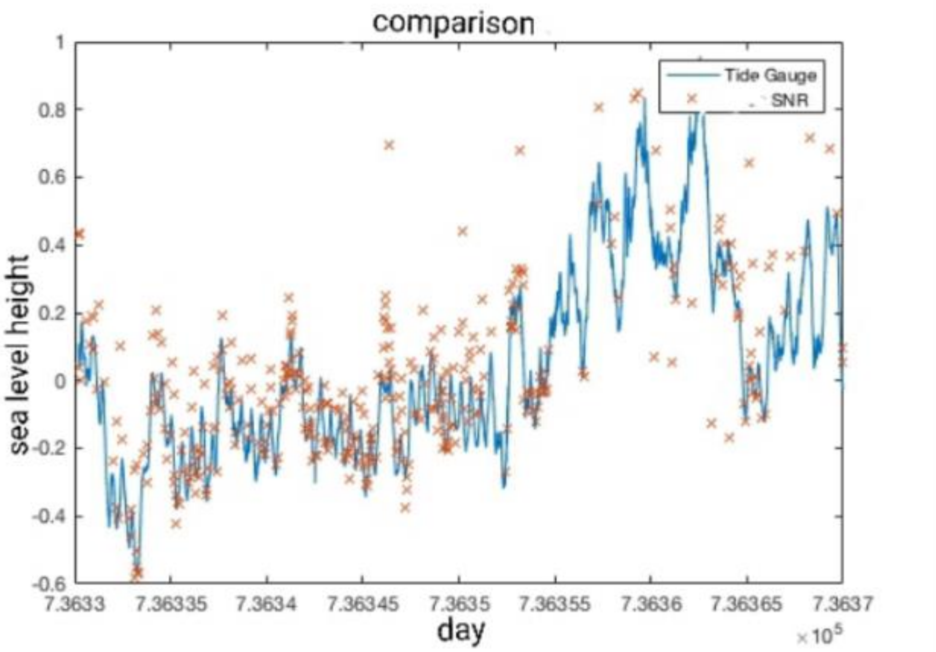

Figure 7 Tide gauge-SNR method sea level height comparison

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5. Conclusion

In this paper, the geometrical relationship and model of shore-based water height measurement based on the signal-to-noise ratio of the satellite navigation reflected signal are constructed. The characteristics of the signal-to-noise ratio (SNR) are analyzed. The function fitting method and the LSP method are used to analyze the antenna receiver. The obtained data height map is compared with the tide gauge. As a result, the SNR analysis method can also use in the other GNSS stations located near the ocean around the world.

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