



Sea Surface Roughness Trends Estimation using Power Waveforms of BeiDou MEO Satellite Reflected Signals

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ABSTRACT

The sea surface is a crucial climate regulator and the boundary where air and water interact. It fuels global weather systems and tempers climate change by absorbing heat and carbon dioxide, while its microscopic marine life generates a major portion of Earth's breathable oxygen. Sea surface roughness monitoring is essential for assessing ocean conditions and improving sea-state and marine weather forecasting. This study proposes a remote sensing approach to characterize sea surface roughness from the power waveforms of BeiDou MEO Satellite Reflected Signals. The waveforms are simulated using a Z-V scattering model, with sea surface slope variances (upwind and crosswind) first derived from a wave spectrum model. The resulting power waveform characteristics, particularly their amplitude patterns, are then analyzed to identify variations in sea surface roughness under different ocean conditions. The results demonstrate a clear relationship between waveform characteristics and sea surface conditions, indicating the potential of GNSS-reflectometry for sea-state monitoring. The findings also provide a basis for future retrieval of other important ocean parameters using reflected GNSS signals.

Keywords: Power waveforms, estimation, sea roughness trend, scattering model, reflected signals

1. Introduction

Sea surface roughness (SSR) is a fundamental geophysical parameter for characterizing ocean surface conditions and plays a significant role in a wide range of marine applications, including oil-spill detection and monitoring (Hu et al. 2009), ocean circulation and dynamics studies (Kudryavtsev et al. 2017), (Kudryavtsev et al. 2012), bathymetric mapping (Zhan et al. 2015), (Gommenginger et al. 1999) and sea-ice monitoring (Landy et al. 2014), (Hong 2010), (Han et al. 2020). However, the highly dynamic and stochastic nature of ocean surface waves makes direct estimation of SSR challenging. Consequently, SSR is often inferred indirectly from measured oceanographic variables, particularly wind speed, through empirical or semi-empirical relationships (Walsh et al. 2005), (Elfouhaily et al. 1997). With advances in remote sensing technology, both active and passive observation techniques have increasingly been adopted for characterizing ocean surface roughness. In particular, microwave radar observations and optical imaging techniques have demonstrated considerable potential for retrieving SSR and associated oceanographic parameters over broad spatial and temporal scales.

Monitoring rapid changes across the ocean surface remains a complex and demanding endeavor. Vulnerability in these regions has escalated due to global climate change drivers, such as polar ice melt, thermal expansion, and shifting oceanic and atmospheric circulation patterns (Bindoff et al. 2007). Furthermore, marine surface roughness receives significantly less research focus than terrestrial roughness, largely due to extreme offshore wind conditions. Unlike land surfaces, ocean roughness is dynamic rather than fixed to wind speed alone; it varies based on wave field characteristics. While several formulations exist to describe this relationship, the Charnock model (Auber et al. 1994), which relies solely on friction velocity remains the standard baseline.

To enhance this formulation, researchers have introduced extra wave field parameters, such as wave age (Beckmann and Spizzichino 1987) or wave steepness (Cox and Munk 1954). Over the past twenty years, Global Navigation Satellite System Reflectometry (GNSS-R) first proposed in 1993 for ocean altimetry (Marchan-Hernandez et al. 2010) has emerged as a robust method for remote sensing (Zavorotny and Voronovich 2000). The primary benefit of GNSS-R lies in its multi-point observational capacity, which yields exceptional spatial and temporal coverage across the globe (Zavorotny and Voronovich 2000). By leveraging signals of opportunity from GNSS constellations, this field has attracted substantial research interest (Arroyo et al. 2014). Operating fundamentally as a bistatic radar, the transmitter and receiver are positioned at substantial distances relative to the surface target (Fabra et al. 2012). When a single receiver captures signals from multiple satellites concurrently, the geometry extends into a multistatic radar system,

which has proven effective for measuring ocean surface roughness (Garrison et al. 2002), (Cardellach et al. 2019). Operating globally in the L-band (1.575 GHz) right next to standard microwave radiometry frequencies, these coded transmissions offer high potential as auxiliary data for surface roughness correction. Theoretical modeling has previously demonstrated and explored this utility (Gleason et al. 2005), (Garrison et al. 1998).

2. Theory

2.1 Geometry of GNSS-R

When satellite signals illuminate the Earth's surface, they scatter across a range of reflection angles dictated by the physical characteristics particularly the roughness of the interface. A perfectly calm water surface produces specular reflection governed by Snell's law, centered at a discrete specular point. On a real, dynamic ocean surface, however, these interactions generate a distributed scattering region known as a glinting zone. The geometry, extent, and power profile of this zone are defined by the prevailing sea state alongside the relative positions of the transmitter and receiver. For instance, microwave signals broadcast by constellations such as BeiDou reflect off the marine surface and are captured by receivers mounted on ground stations, aircraft, or Medium Earth Orbit (MEO) satellites. Within GNSS Reflectometry (GNSS-R), these active scattering regions are mapped and discretized into fundamental resolution cells using delay chips and Doppler frequency bins.

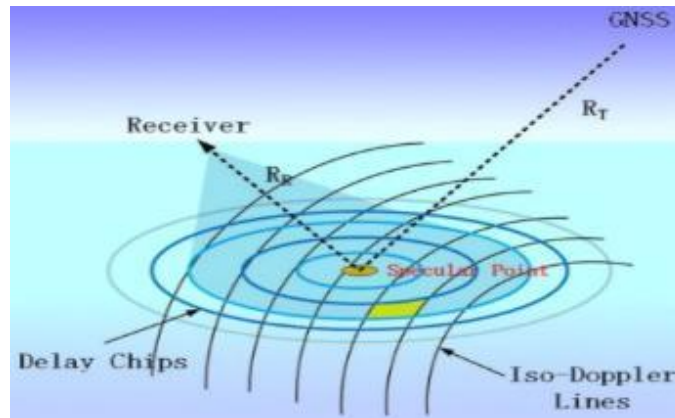


Fig. 1 - The Geometry of GNSS-R (Harigae et al. 2005)

2.2 The Wave Spectrum Model

The Elfouhaily wave spectrum is expressed as a function of the wavenumber (k), the 10-m wind speed (U_{10}), and the azimuthal angle ϕ , as given in Equation (1). The formulation incorporates contributions from both the low- and high-frequency components of the ocean wave spectrum, denoted by the subscripts (l) and (h), respectively. In this formulation, (B_l) represents the spectral curvature associated with the long-wave component, whereas (B_h) denotes the corresponding curvature for the short-wave component. The parameter Delta represents the unified directional spreading function, which describes the angular distribution of wave energy with respect to the wind direction.

$$\Psi(k, U_{10}, \phi) = \frac{1}{2\pi} K^{-4} [B_l(U_{10}) + B_h(U_{10})] [1 + \Delta(k, U_{10}) \cos(2\phi)] \quad \dots\dots\dots(1)$$

2.3 The Scattering Model

To accurately model GNSS-R signal variations, simulating the coherent power scattered off the ocean surface is essential. This relies heavily on the scattering coefficient, which captures sea surface roughness. In this study, we utilize the bistatic scattering model grounded in the Kirchhoff Approximation under the Geometric Optics (KA-GO) limit. The general expression for this model is defined as follows:

$$\langle Z(\Delta_r, \Delta_f) \rangle \propto \iint_D \frac{G_r(r)}{R_G^2(r) R_R^2} \frac{q^4}{q_z} P\left(-\frac{q^\perp}{q_z}\right) * \Lambda^2(\tau(r) - \Delta_r) \theta^2(f(r) - \Delta_f) dr \quad \dots\dots\dots(2)$$

here, r represents the spatial coordinates on the sea surface, G_r denotes the gain of the down-looking receiving antenna, and q is the scattering vector. Ocean surface slope dynamics are characterized by the probability density function P , while Λ describes the delay autocorrelation function of the transmitted ranging code. Furthermore, Y accounts for frequency modulation resulting from height fluctuations across the random sea surface. Finally, R_G and R_R indicate the geometric distances from the scattering point to the GNSS satellite and the receiver, respectively.

3. Methodology

3.1 Data Collection

To capture raw direct and specularly reflected BeiDou signals under diverse environmental conditions, a field campaign was carried out near the Bohai Sea coast in Shandong, China. The observation site was positioned on a wharf roughly 7 km from the shoreline (38.1541-degree N & 119.0655-degree E). Stationed 40 m above MSL, the receiver utilized an LHCP antenna pointed toward an azimuth of 210 degree with an elevation/tilt angle of 45 degree relative to the horizontal ocean surface.

3.2 Data Processing Receiver

Raw data processing was executed using a modified version of the open-source MATLAB package, GPS MATLAB Tools (developed by Kai Borre at Aalborg University), customized to handle the specific raw bitstream structure. The 8-bit sample format allocates the first two bits to direct signals and the following two bits to reflected signals, repeating this 4-bit pair structure for subsequent samples. The tracking stage extracts satellite transmission metadata and yields in-phase (I) and quadrature (Q) components, which serve as essential inputs for constructing power waveforms.

Signal acquisition successfully identified 10 Beidou satellites. The PRN of acquiring satellites is 02, 04, 05, 07, 08, 09, 10, 13, 26 & 29 that means 10 (ten) satellites are visible in that moment. This acquisition result is performed for Beidou GEO satellite. Figure 2 illustrates the tracking performance specifically for PRN 29. Here, the green bars are indicated the acquired satellites and blue bars represented not acquired satellites.

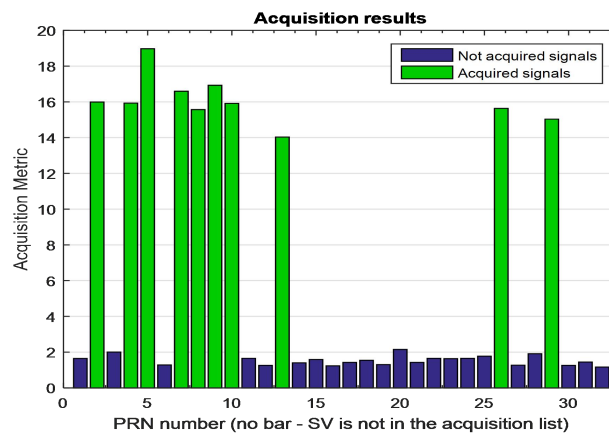


Fig. 2 - Satellites acquisition results

3.3 Power Waveforms Generation Technique

The principle of power waveforms generation based on I and Q signals. When, it is performed the tracking of GNSS satellite, the tracking results are provided values of I and Q signals. The following I and Qs information of direct and reflected signals is provided. From GNSS tracking results, it is found the I and Q signals: For Direct Signal: I_d & Q_d and for reflect signal: I_r & Q_r and for both it is found the prompt, early and late signals are: I_P , I_E , I_L and Q_P , Q_E , Q_L .

The power waveform can be calculated by using these I and Qs of direct and reflected signals. The generation principle of power waveform depends on the values of I and Q signals. The tracking results provide the information of I and Q signals from direct and reflected GPS signals. For direct and reflected signals, it is represented as I_d & Q_d and I_r & Q_r respectively. The early, prompt and late signals are I_P , I_E , I_L and Q_P , Q_E , Q_L for both direct and reflected signals. The power waveform can be calculated by using value of I and Q of direct and reflected signals. The principle of power waveforms generation is shown in figure 8. From raw data to power waveforms, the whole process is designed my MATLAB.

The Elfouhaily wave spectrum is expressed as a function of the wavenumber (k), the 10-m wind speed (U_{10}), and the azimuthal angle ϕ , as given in Equation (1). The formulation incorporates contributions from both the low- and high-frequency components of the ocean wave spectrum, denoted by the subscripts (l) and (h), respectively. In this formulation, (B_l) represents the spectral curvature associated with the long-wave component, whereas (B_h) denotes the corresponding curvature for the short-wave component. The parameter Delta represents the unified directional spreading function, which describes the angular distribution of wave energy with respect to the wind direction.

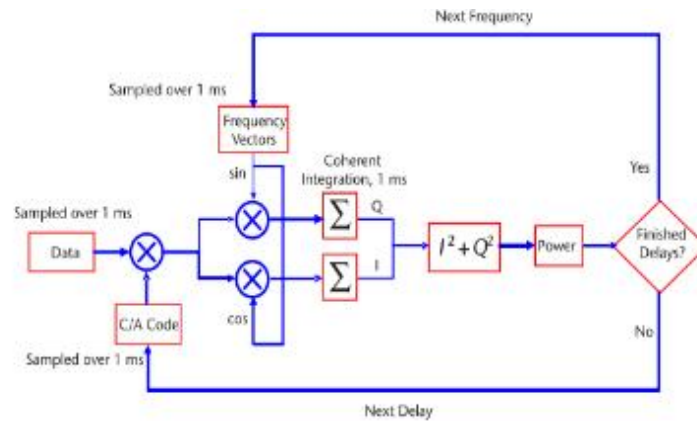


Fig. 3- Power waveforms generation model

3.4 Technique of Sea Surface Roughness Trend Measurement

For sea-roughness determination, the power waveforms obtained from Beidou MEO satellite data and the proposed model were analyzed with respect to coherent integration time, wind speed, and satellite elevation angle. The results indicate that both the shape and amplitude of the waveforms are sensitive to these three parameters. The observed relationships between waveform amplitude and the three parameters can be expressed as

$$A \propto T^n \quad \dots\dots\dots (3)$$

$$A \propto \frac{1}{W^n} \quad \dots\dots\dots (4)$$

$$A \propto \theta^n \quad \dots\dots\dots (5)$$

where A is the waveform amplitude,

T is the coherent integration time,

W is the wind speed,

θ is the satellite elevation angle, and $n=0,1,2,\dots\dots$.

If ($n=0$), the combined relationship is obtained as:

$$A = \frac{KT\theta}{W} \quad \dots\dots\dots (6)$$

where K is a non-zero constant. This combined relationship was subsequently used to develop the proposed model for estimating sea-surface roughness trends.

Results and Analysis

4.1 Results of Power Waveforms from Beidou MEO Satellite Data

This section presents the power-waveform characteristics obtained from the BeiDou Medium Earth Orbit (MEO) satellite signals. Direct and reflected signals from the selected MEO satellite PRN are processed to generate their corresponding power waveforms. The waveforms are examined for several coherent integration intervals, namely 1, 10, 50, and 100 ms. In the presented figures, the waveform amplitude is plotted along the y-axis, whereas the x-axis denotes the signal delay in chips.

The waveform characteristics are investigated considering three principal parameters: (i) coherent integration time, (ii) wind speed, and (iii) satellite elevation angle. These parameters are selected because variations in signal integration and propagation conditions can produce noticeable changes in the amplitude and overall characteristics of the received power waveform.

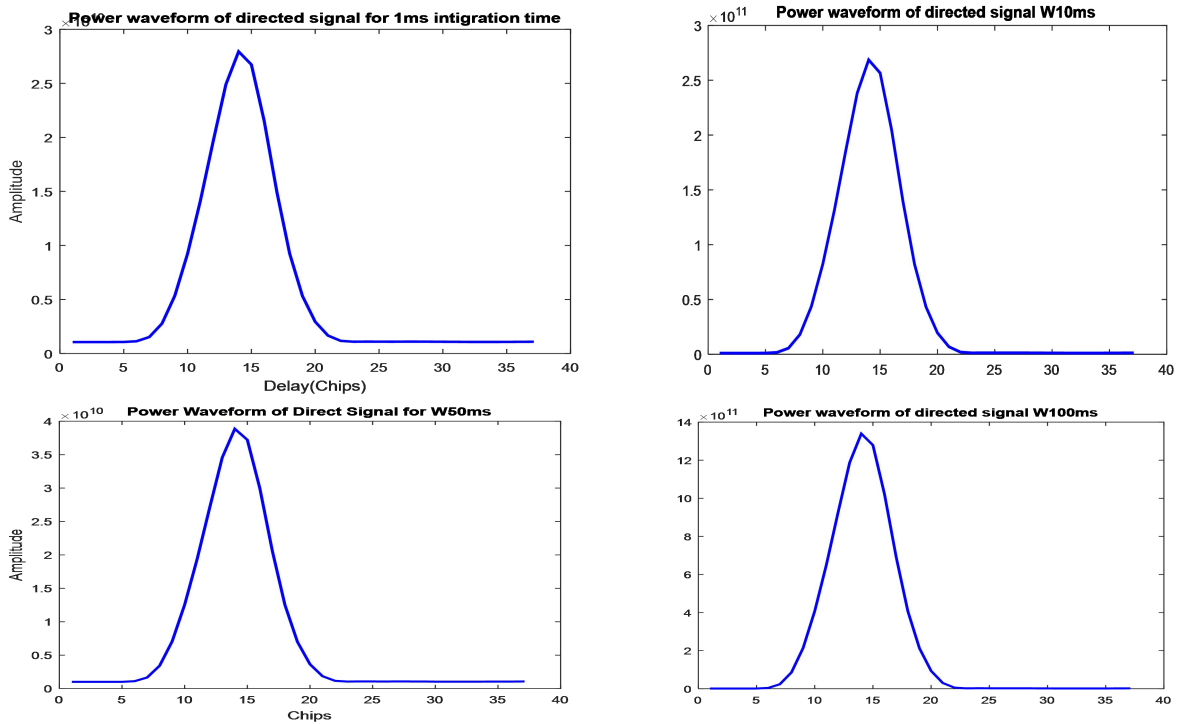


Fig 4 - Power Waveforms of 1ms, 10ms, 50ms & 100ms for direct signals (2015_08_26_14_49_54)

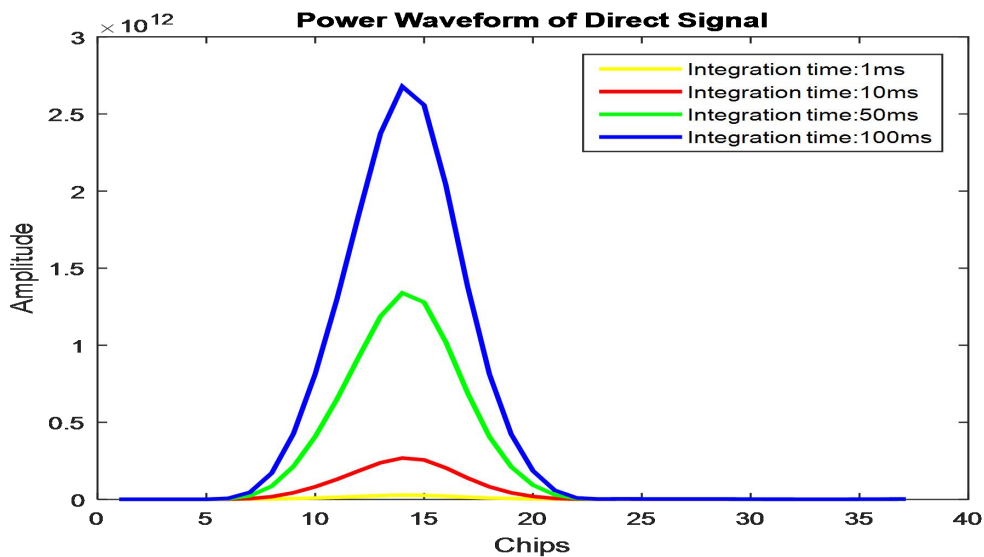


Fig 5 - Power waveforms of direct signal for different integration times (1ms, 10ms, 50ms & 100ms)

Figures 4 and 6 show the power waveforms corresponding to the direct and reflected MEO signals, respectively, for different coherent integration times. The associated combined waveform results are presented in Figures 5 and 7. These figures compare the waveform responses obtained using integration periods of 1, 10, 50, and 100 ms, allowing the effect of integration time on the received signal power to be clearly observed. The results demonstrate a consistent increase in waveform amplitude as the coherent integration time is increased. This behavior is observed for both the direct and reflected signals. Among the four integration intervals, the 100-ms case produces the highest waveform amplitude, while the 1-ms case exhibits the lowest amplitude. The 10-ms and 50-ms results show intermediate responses, following the same overall trend.

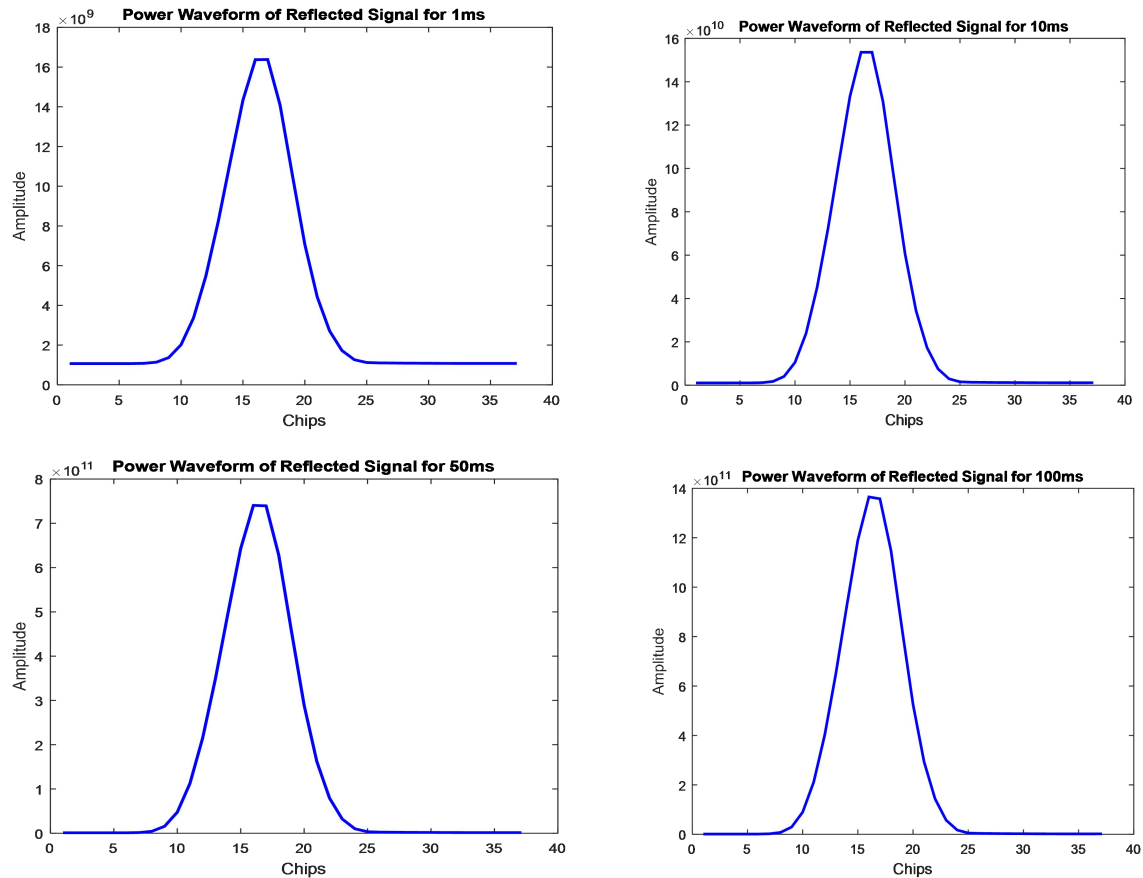


Fig 6 - Power Waveforms of 1ms, 10ms, 50ms & 100ms for reflected signals

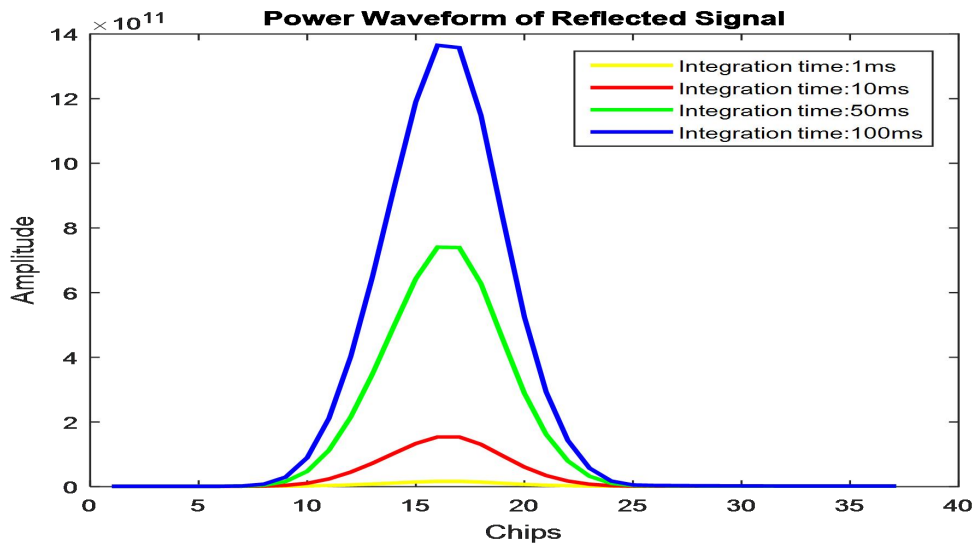


Fig 7 - Power waveforms of reflected signal for different integration times (1ms, 10ms, 50ms & 100ms)

The combined waveform plots in Figures 5 and 7 further illustrate this dependence on integration time. Although the general waveform structure remains recognizable, its amplitude becomes progressively stronger with longer integration periods. Therefore, the results confirm that coherent integration time has a significant influence on the power level of the BeiDou MEO waveform. In particular, the substantially higher amplitude obtained at 100 ms compared with 1, 10, and 50 ms demonstrates the importance of integration time when analyzing the characteristics of direct and reflected GNSS signals for sea-surface roughness assessment.

To investigate the effect of wind speed on the reflected GNSS signal, power waveforms were generated using BeiDou MEO satellite data under different wind-speed conditions. The results are presented in Figure 8 for four wind speeds: 2.0, 2.5, 3.2, and 3.6 m/s. The results show a clear dependence of the reflected waveform amplitude on wind speed. As the wind speed increases, the amplitude of the reflected power waveform gradually

decreases. At a lower wind speed, the sea surface is relatively smoother, resulting in a stronger and more coherent reflected signal. Consequently, the waveform exhibits a higher peak amplitude and a shape closer to the autocorrelation function.

In contrast, higher wind speeds produce greater sea-surface roughness, which causes increased scattering and reduces the coherent component of the reflected signal. This results in a lower waveform amplitude and a less pronounced correlation peak. Therefore, Figure 8 demonstrates an inverse relationship between wind speed and reflected waveform amplitude, indicating that waveform characteristics can be used to assess variations in sea-surface roughness.

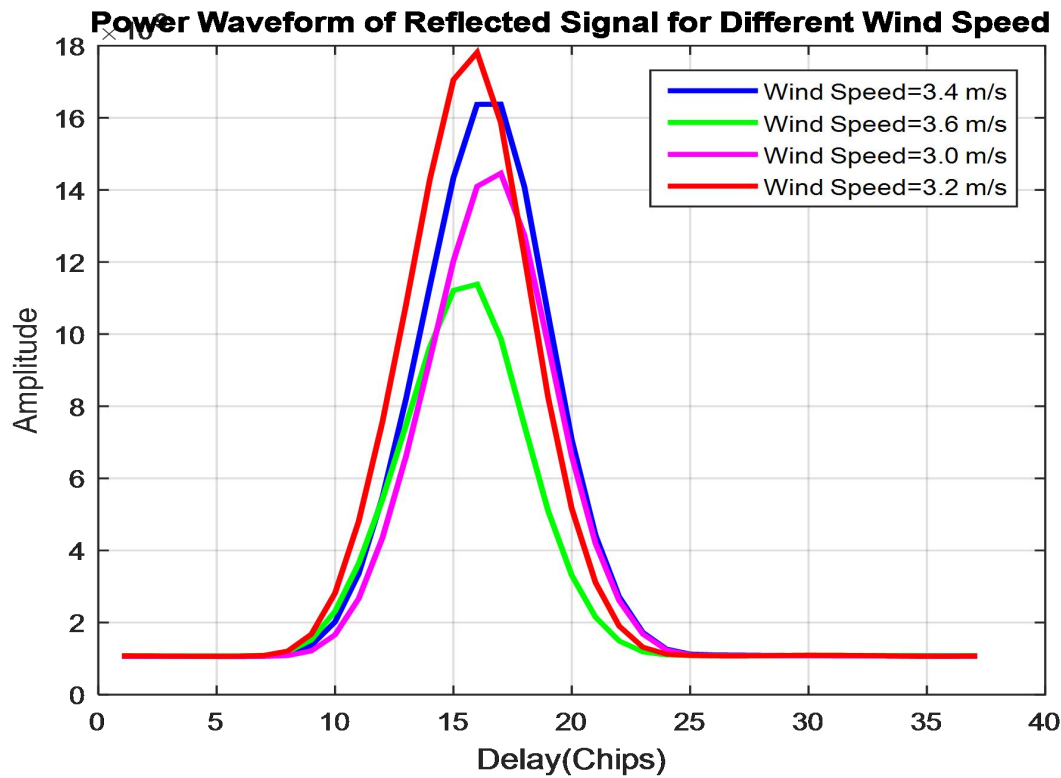


Fig 8 - Power waveforms of reflected signals for different wind speed

4.2 Results of Power Waveforms from Model

Two theoretical models are employed to simulate the power waveforms associated with sea-surface scattering. First, the wave-spectrum model is used to characterize the statistical properties of the sea surface and to estimate the corresponding surface-slope variances. These variances are then provided as inputs to the scattering model, which calculates the reflected signal and generates the simulated power waveforms.

To investigate the influence of sea-state conditions, the simulated waveforms are evaluated for wind speeds of 5, 10, 15, 20, and 25 m/s, as illustrated in Figure 9. A clear variation in waveform amplitude is observed with changing wind speed. The waveform amplitude is highest at 5 m/s and gradually decreases as the wind speed increases, reaching its minimum value at 25 m/s.

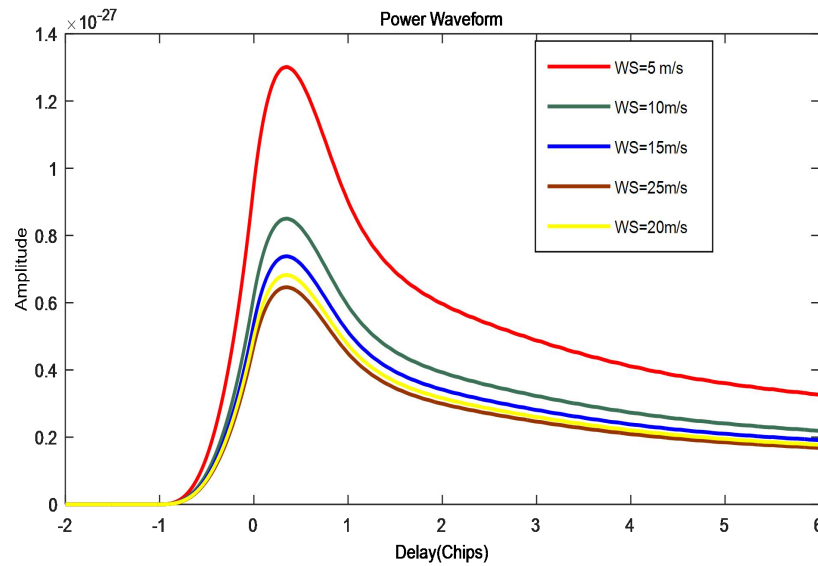


Fig 9 - Model power waveforms of different wind speeds

This behavior can be attributed to the increasing roughness of the sea surface under stronger wind conditions. At relatively low wind speeds, the sea surface is comparatively smooth, allowing a larger coherent component of the reflected signal to be received. Consequently, the resulting waveform has a distinct and relatively high correlation peak. As wind speed increases, enhanced surface roughness causes greater signal scattering and reduces the coherent reflected power, leading to a reduction in waveform amplitude.

The waveform shape also changes with wind speed. At lower wind speeds, the simulated waveform more closely resembles the autocorrelation function (ACF), whereas the correlation peak becomes less pronounced under higher wind conditions. These results demonstrate that the simulated power waveform is strongly dependent on wind speed and can therefore provide a useful indicator of variations in sea-surface roughness.

4.3 Results of Sea-Surface Roughness Trend

The power waveforms obtained from the direct and reflected Beidou satellite signals are compared to investigate their respective characteristics and their applicability to sea-surface roughness estimation. The analysis shows that the direct signal generally produces a higher waveform amplitude than the reflected signal. However, the overall waveform profiles of the two signals exhibit similar characteristics, particularly in terms of their correlation behavior. Under relatively calm sea conditions, the reflected waveform retains a well-defined correlation structure and tends to resemble the autocorrelation function of the transmitted signal. As the sea surface becomes rougher, surface scattering increases, resulting in a reduction in the coherent component of the reflected signal and a corresponding change in waveform amplitude and shape.

The simulated waveforms generated by the proposed model exhibit somewhat different characteristics from the measured GPS waveforms. In particular, the model-generated waveform does not always maintain a smooth profile. This difference can be associated with the antenna gain pattern and its influence on the received reflected signal, which may shift or broaden the waveform response toward larger signal delays. Based on these observations, the sea-surface roughness trend is determined by examining the combined effects of three important parameters: coherent integration time, wind speed, and satellite elevation angle. The established relationships between waveform amplitude and these parameters are used to characterize changes in the reflected signal associated with different sea-surface conditions. By applying these relationships to the measured and simulated waveform responses, the corresponding trend of sea-surface roughness is estimated. The resulting roughness trends obtained from the analysis are summarized in Table 1.

Table 1 - Sea Surface Roughness Trend Estimation

Parameter	Positive Variation	Negative Variation	Overall Relationship with Roughness
Coherent Integration Time	Higher amplitude → Increasing roughness	Lower amplitude → Decreasing roughness	<i>Direct</i>
Wind Speed	Lower amplitude → Decreasing roughness	Higher amplitude → Increasing roughness	<i>Inverse</i>
Satellite Elevation Angle	Higher amplitude → Increasing roughness	Lower amplitude → Decreasing roughness	<i>Direct</i>

Conclusion

A waveform-based technique has been developed for estimating the trend of sea-surface roughness from GNSS reflected signals. The proposed approach characterizes waveform amplitude in relation to three key parameters: coherent integration time, wind speed, and satellite elevation angle. The analysis establishes that waveform amplitude increases with integration time and satellite elevation, while decreasing with wind speed. These relationships are incorporated into a unified model to estimate variations in sea-surface roughness. The reliability of the proposed method is evaluated using field observations, including wind speed and sea-wave height recorded during the data-collection campaign. The estimated roughness trends show good agreement with the corresponding real sea-surface conditions, demonstrating the potential of the proposed technique for GNSS-based monitoring of sea-surface roughness.

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