

Modeling and analysis of monostatic surface reverberation intensity under the action of sea surface wind speed in deep water

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Abstract Ocean reverberation is one of the main background interferences of active sonar. When both the transmitting and receiving transducers are located near the sea surface, the first received reverberation signal is surface reverberation, and the total reverberation is not affected by the seabed scattering sound field. Considering that the surface reverberation intensity is affected by the surface wind speed, this paper constructs a two-dimensional (2D) monostatic surface reverberation theoretical model that introduces the surface undulation environment. Combined with a 3D dynamic surface undulation model based on the bimodal spectrum of wind waves and swell, the influence of surface undulation under the action of wind speed on the surface reverberation intensity is studied. The results show that the degree and consistency of surface undulation in the downwind direction are significantly higher than those in the crosswind direction, resulting in the direction dependence of the reverberation intensity. Under high wind speeds, the reverberation intensity in the downwind direction is significantly increased by the multipath effect of the undulating sea surface.

Keywords Deep water, Surface reverberation, Surface roughness, Wind speed, Active sonar

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1 Introduction

For active sonar, reverberation, as a random signal with certain characteristics, is the primary interference source for target signal detection^[1-3]. Meanwhile, the ocean reverberation carries rich environmental information, providing an important basis for parameter inversion, such as sea surface roughness and bottom geoacoustic properties^[4,5]. In deep water environments, early reverberation is typically dominated by sea-surface contributions. When the source and receiver are located between the surface and bottom interfaces, often closer to the surface, the sea surface reverberation arrives before the seabed reverberation in time after the direct wave signal, thereby becoming the dominant component.

As a part of ocean reverberation, many studies have been carried out on sea surface reverberation^[6-8]. Schneider^[9] employed a split-step parabolic wave equation model to calculate surface loss, scattering, and reverberation, and proposed a computation method applicable to range-dependent environments. Gao *et al.*^[10] investigated surface reverberation

in shallow water caused by a rough surface under different sea states using coupled mode theory. Qi *et al.*^[11] generated rough sea surfaces using the Pierson–Moskowitz (PM) spectrum and compared common roughness scattering theories for sea surface acoustic backscattering at intermediate frequency range. The results show that different roughness scattering theories can accurately be predicted only under specific conditions. Yin *et al.*^[12] further used a first-order small-slop approximation (SSA) to characterize sea-surface scattering over a wide angular range and derived a surface reverberation model.

Although significant progress has been made in the study of reverberation scattering mechanisms and theoretical modeling, most existing studies still rely on idealized or two-dimensional (2D) environmental models. Investigations into 3D rough sea surfaces jointly driven by wind waves and swell, and their impacts on the directional characteristics and intensity structure of reverberation, remain limited. Therefore, it is necessary to further develop 3D reverberation modeling and mechanistic analysis for complex deep water

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environments. The main contributions of this study are summarized as follows.

The prediction of sea surface undulation based on a single wind speed parameter was achieved by using wind speed, significant wave height of wind waves and swell, and their angle relationships from the public database ERA5, which is provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). A 3D dynamic sea surface undulation model based on the double-peak spectrum of wind waves and swell was constructed, and the anisotropic characteristics of sea surface reverberation intensity were studied accordingly.

2 Mathematical model

2.1 Sea surface reverberation modeling

2.1.1 Surface reverberation model

Reverberation is a highly complex acoustic phenomenon involving propagation, scattering, and multipath effects. It is extremely difficult to directly perform precise modeling. Therefore, in order to focus on the main influencing factors and simplify the analysis, when discussing reverberation, this paper makes the following basic assumptions about the relevant physical processes^[13]:

- (1) Consider the influence of the sound-speed gradient, the attenuation of spherical waves, and absorption loss of seawater, and ignore the attenuation caused by other factors;
- (2) Scatterers located in a certain area at any instant are always randomly and uniformly distributed;
- (3) Only single scattering is considered, while multiple scattering among scatterers is neglected;
- (4) The received scattered waveform is assumed to remain consistent with the waveform emitted by the sound source.

Based on the aforementioned assumptions, the modeling and characterization of sea-surface reverberation are discussed.

Sea surface reverberation is mainly caused by the scattering of sound waves by the near-surface bubble layer formed under the action of wind waves and the undulating sea surface. A schematic representation of the scattering cell distribution of monostatic surface reverberation is provided below. Under wind-wave disturbances, bubbles near the sea surface are distributed within a water layer of finite thickness. As shown in Fig. 1(a), the height of the bubble layer is assumed to be H . Considering a monostatic configuration where the source and receiver are co-located at point O , we assume that the pulse width of the emission is τ , and the sound speed is c . According to the spherical spreading assumption, this sound pulse forms a perturbed spherical shell with a thickness of $c\tau$ in the medium. Consequently, at a certain moment, the area contributing to the reverberation is a

spherical frustum-shaped annulus with a height H and a radial width of $c\tau/2$, as illustrated by the shaded region in Fig. 1. Here, r denotes the range from the sound source to the annulus, R denotes the horizontal distance from the sound source to the inner side of the circular ring of the scattering layer, h represents the vertical depth from the sound source to the sea surface scattering layer.

The circular ring gradually moves outward over time, and its area gradually increases, resulting in a gradual increase in the number of scatterers that produce reverberation.

The circular ring gradually expands outward over time, and its area increases accordingly. This leads to a gradual rise in the number of scatterers responsible for generating reverberation.

The equivalent plane-wave expression for the sea-surface reverberation level is

$$RL = SL - (20\lg(r)) + S_s + 10\lg\left(\frac{c\tau}{2}r\Phi\right) - 2ra, \quad (1)$$

where RL denotes the equivalent plane-wave reverberation level, SL denotes the source level, and $20\lg(r)$ represents spherical expansion loss. S_s denotes the interface scattering strength, and Φ denotes the combined directivity pattern of the transmitting and receiving transducers. $10\lg((c\tau/2)r\Phi)$ represents the correction term associated with the scattering area and transducer directivity. α denotes the acoustic absorption coefficient in seawater. In the special case of a non-directional transducer, $10\lg\Phi = 10\lg(2\pi) \approx 8$.

2.1.2 Sea-surface scattering model

From the equivalent plane-wave reverberation-level formulation, the interface scattering S_s should be obtained first before calculating the sea surface reverberation level RL . Therefore, the analysis of sea-surface reverberation can

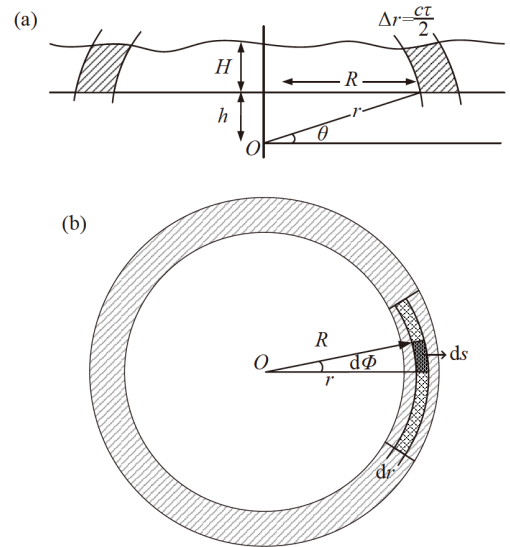


Fig. 1 Schematic representation of scattering cell distribution for monostatic sea-surface reverberation: (a) Side view; (b) Top view.

be formulated as the problem of accurately modeling the sea-surface acoustic scattering process. The SSA can cover all incident and scattering angles within a single approximation, offering a broad regime of applicability. Therefore, the Gaussian SSA (Gauss-SSA) is employed in this work^[14].

In the dynamic air-sea boundary layer, scattering processes exhibit considerable complexity. When wave breaking is pronounced, scattering from the rough air-sea interface is superimposed with subsurface bubble scattering. In the absence of wind and wave agitation, the scattering strength per unit area of the sea surface can be expressed as

$$S_s = 10 \lg \sigma_{\text{surf}}, \quad (2)$$

where the sea-surface scattering cross section per unit area σ_{surf} denotes a physical parameter that characterizes the scattering behavior of a randomly rough air-sea interface, which is

$$\sigma_{\text{surf}} = \frac{1}{8\pi} \left| \frac{\beta}{|Q_h Q_z|} \right|^2 \cdot I, \quad (3)$$

where β denotes the sea-surface boundary condition coefficient, and $\beta = -4k_0^2 \sin \theta_{\text{inc}} \sin \theta_{\text{scat}}$, in which θ_{inc} and θ_{scat} are the grazing angles of the incident and scattered waves, respectively, and k_0 denotes wavenumber, defined as $k_0 = 2\pi f / c_0$ (c_0 is the average sound speed). Q_h and Q_z represent the differences between the horizontal and vertical components of the incident and scattered wave vectors, respectively, which are determined by the scattering geometry. I denotes the roughness spectrum integral.

Gauss *et al.*^[14] proposed a model for describing the bubble-layer scattering cross section per unit area σ_{bub} based on a large amount of deep-sea scattering measurement data.

$$\sigma_{\text{bub}} = \frac{0.0019 d^{5.15} k_0^{-0.6} k_{v,i}^2 k_{v,s}^2 \left[6 + 3(k_{v,i}^2 + k_{v,s}^2) d^2 + (k_{v,i}^2 - k_{v,s}^2)^2 d^4 \right]}{2(1 + k_{v,i}^2 d^2)(1 + k_{v,s}^2 d^2) \left[1 + (k_{v,i} - k_{v,s})^2 d^2 \right] \left[1 + (k_{v,i} + k_{v,s})^2 d^2 \right]}, \quad (4)$$

where $k_{v,i} \equiv -k_0 \sin \theta_{\text{inc}}$ and $k_{v,s} \equiv -k_0 \sin \theta_{\text{scat}}$. d represents the attenuation depth of the bubble layer, characterizing the characteristic depth over which the void fraction within the bubble cloud decays exponentially with increasing water depth. This parameter is related to the wind speed U measured at a height of 10 m above the sea surface, and its value can be estimated using the following empirical relationship:

$$d = \begin{cases} 0.557 - 0.117U + 0.0109U^2, & U > 7.5 \text{ m/s}, \\ -0.19509 + 0.06503U, & 3 \leq U \leq 7.5 \text{ m/s}, \\ 0, & U < 3 \text{ m/s}. \end{cases} \quad (5)$$

Therefore, when the contribution of the bubble cloud is taken into account, a more accurate expression for the total sea-surface scattering strength per unit area can be written as

$$S_s = 10 \lg(\sigma_{\text{surf}} + \sigma_{\text{bub}}). \quad (6)$$

The surface scattering cross section σ_{surf} is governed by the parameter I , which depends on the sea-wave spectrum amplitude parameter A_s .

A_s is further controlled by the U , as wind-driven processes modulate the sea-surface roughness and thereby affect the value of I . Meanwhile, the U also determines the attenuation depth d of the bubble layer, which in turn influences the bubble-cloud scattering cross section σ_{bub} . Gauss *et al.*^[14] obtained A_s ($1.9 \times 10^{-4} \text{ m}^3 \cdot \text{s}$) and γ_x^2 (3.8) through fitting a large amount of measured data. Using these empirical parameters, the expression for the surface scattering strength S_s can be further simplified as

$$S_s = 10 \lg(\sigma_{\text{surf}}(U) + \sigma_{\text{bub}}(U)). \quad (7)$$

Based on Eq. (7), this study computes the sea-surface reverberation level and investigates the effects of wind speed on sea-surface roughness and reverberation intensity.

2.1.3 Element scattering model

Two approaches are commonly adopted for reverberation modeling, namely the point-scatterer model and the element scattering model. Compared with the point-scatterer model, the cell-based formulation exhibits lower computational complexity and is therefore more broadly applicable in engineering practice. In this study, the reverberation is simulated using the cell-based scattering model, and the corresponding simulation procedure is outlined as follows.

Since the arrival times of sound signals at each scatterer are different, the arrival times of the scattered echoes generated by the scatterers at the receiving point are also different. Assuming that the waveform of the scattered echo signal generated by the scatterer is consistent with the transmitted signal, the reverberation signal at the receiving point can be regarded as the result of superimposing the transmitted signal after different time delays.

In the monostatic surface reverberation model, the characteristics of different scattering paths are assumed to be statistically independent. Under the principle of linear superposition, and according to Eq. (1) and the definition of reverberation, N denotes the number of scattering cells contributing at time t ; the reverberation signal can then be expressed as Eq. (8) by time-aligning and summing the individual contributions:

$$y(t) = \sum_{i=1}^N p_{ri} p_{si} \times S_s(\theta_{ri}, \theta_{si}) x(t - \tau_i) e^{j\varphi_i}, \quad (8)$$

where p_{si} denotes the sound pressure amplitude from the source to the i th scattering cell. p_{ri} denotes the sound pressure amplitude from that scattering cell to the receiver. p_{si} and p_{ri} all account for reflection and propagation losses. $S_s(\theta_{si}, \theta_{ri})$ denotes the backscattering function. $x(t - \tau_i)$ is

the transmitted signal with a time delay of τ_i , where τ_i corresponds to the difference between the total acoustic path from the transmitting and receiving arrays to the scattering unit and the acoustic path of the reference unit, that is, the arrival time of the reverberation component. φ_i is a random phase subject to a uniform distribution.

Scatterers contributing to sea-surface reverberation are distributed across an annular region of finite thickness centered at the source. Within the transmit angular range, the sea surface corresponding to the source–scatterer distance is discretized into N_r range. The subscript “r” indicates division according to the range. Due to the non-uniformity and anisotropy of reverberation within the receiving fan cause different scattering intensities in various directions, the contributing sector is further subdivided into N_a segments. The subscript “a” indicates division according to the angle. For an individual scattering cell, the sea-surface reverberation is approximated as the superposition of echoes from $N_a \times N_r$ scattering elements. Consequently, the total reverberation is formulated as the aggregate summation of contributions from a total of $N \times N_a \times N_r$ scattering elements across all array elements:

$$Y(t) = \sum_{i=1}^N \sum_{j=1}^{N_a} \sum_{k=1}^{N_r} y_{j,k}(t), \quad (9)$$

where $Y(t)$ denotes overall reverberation signal.

2.2 Modeling of undulating sea surface

Traditional sea surface models usually assume that the sea surface undulations follow a Gaussian process. However, due to the nonlinear wave-wave interactions, the actual sea surface fluctuations often exhibit non-Gaussian characteristics^[15].

2.2.1 3D dynamic sea wave modeling

To characterize sea-surface undulations, a reference plane (x, y) is first defined, and the height of a point on the surface is represented as $z(x, y)$. Second, to comprehensively describe the dynamic characteristics of waves, it is also necessary to introduce the time dimension to reflect the evolution process of waves over time. In this context, the Gerstner wave model, as a classic wave description method, provides an effective mathematical tool for the simulation of ocean waves.

The wave surface formula of the Gerstner wave model can be expressed as

$$z(x, y, t) = \sum_{i=1}^M \sum_{j=1}^N A_{ij} \cos[k_i(x \cos \alpha_{dj} + y \sin \alpha_{dj}) - \omega_{di}t + \beta_{ij}], \quad (10)$$

where A_{ij} , k_i , α_{dj} , ω_{di} , and β_{ij} denote the wave amplitude, wavenumber, direction angle, angular frequency, and phase, respectively. Based on linear wave theory, the relationship between k_i and ω_{di} is given by $k_i = \omega_{di}^2 / g$, where

g ($g = 9.8 \text{ m/s}^2$) is the gravitational acceleration. x , y , and t represent the spatial coordinates and time, respectively, and z denotes the resulting surface elevation. In practical implementations, the direction angle and angular frequency are discretized, while the remaining parameters are determined accordingly for different direction angles and angular frequency components^[16].

The instantaneous wave elevation can be obtained by superposing the amplitudes of component waves with discretized angular frequencies ω_{di} and direction angles α_{dj} at the spatial location (x, y) and time t . The subscript “d” represents selecting the center of the divided segment. N and M denote the number of direction angles and angular frequency partitions, respectively. The propagation direction angle α is restricted to $[\alpha_{\text{main}} - \pi/2, \alpha_{\text{main}} + \pi/2]$ and is uniformly discretized into N bins with an angular spacing of $\Delta\alpha = \pi/(N-1)$, the bin-center values are taken as α_{dj} . In this study, the wind-wave direction is used as α_{main} , and N is set to 20.

Spectral analysis provides an alternative statistical description of a wave train. In this approach, the distribution of wave energy is represented as a function of frequency. Using a prescribed wave spectrum, the wave amplitude A_{ij} can be determined by

$$A_{ij} = \sqrt{2S(\omega_{di}, \alpha_{dj})\Delta\omega\Delta\alpha}, \quad (11)$$

where $S(\omega_{di}, \alpha_{dj})$ denotes the directional wave spectrum, representing the wave energy density at angular frequency ω_{di} and propagation direction α_{dj} .

2.2.2 Bimodal spectrum of wind waves and swell

The JONSWAP spectrum is obtained by modifying the PM spectrum, in which the spectral shape is parameterized by the peak angular frequency ω_p and the peak enhancement factor γ ^[17]:

$$S_w(\omega) = C \left(\frac{\omega}{\omega_p} \right)^{-5} \exp \left[-1.25 \left(\frac{\omega}{\omega_p} \right)^{-4} \right] \cdot \gamma \exp \left(-(\omega - \omega_p)^2 / 2\sigma^2 \omega_p^2 \right), \quad (12)$$

$$\begin{cases} \sigma = 0.07, & \omega \leq \omega_p \\ \sigma = 0.09, & \omega > \omega_p \end{cases} \quad (13)$$

$$\omega_p = 22 \frac{g^2}{UF}, \quad (14)$$

where F denotes the fetch length that is the distance over which the wind blows at a constant speed (fixed at 100 km), U denotes the mean wind speed at 10 m above the mean sea surface, and the constant C is determined from the significant swell wave height H_s as

$$C = \frac{5H_s^2}{16\omega_p} \left(1.15 + 0.1688\gamma - \frac{0.925}{1.909 + \gamma} \right)^{-1}. \quad (15)$$

The variables used are the significant wave height of the swells and the wind speed in the fitting between the theoretical JONSWAP spectrum and the measured swells. Among them, the spectral peak enhancement factor takes the average value as a fixed parameter $\gamma = 3.3$.

A bimodal spectrum was then modeled as the superposition of two wave systems (wind sea and swell), whose spectra and peak periods were specified independently; accordingly, the combined spectrum was expressed as denote the wind-sea $S_w(\omega)$ and swell $S_s(\omega)$ spectra:

$$S(\omega) = S_s(\omega) + S_w(\omega). \quad (16)$$

In realistic marine environments, multiple swell systems may coexist, comprising both primary and secondary swells. The primary swell typically exerts the most significant influence on sea states, as it is characterized by larger wave heights and longer periods. Consequently, only the combination of the primary swell and wind-driven waves is considered in this study.

3 Simulation analysis

3.1 Surface reverberation simulation

3.1.1 Surface reverberation simulation procedure

Based on the deep reverberation model in Eq. (9) presented above, the simulation procedure for time-domain reverberation signals is outlined as follows.

First, the simulation is conducted within a monostatic transceiver configuration, incorporating essential environmental parameters such as ocean depth, surface roughness characteristics, and sound speed profiles.

Second, to streamline the computation of reverberation contributions from individual units, the ocean surface is discretized into multiple azimuthal sector cells based on the principles of the cell scattering model. Each cell represents an ensemble of scatterers, thereby simplifying the calculation of scattering characteristics and propagation path losses.

Finally, the contributions from these cells are superimposed chronologically according to their respective time delays and convolved with the input acoustic signal to synthesize the final reverberation.

In deep water reverberation research, ray acoustics theory is typically employed to describe sound propagation due to the limited number of boundary reflections and scatterings. In this study, the Bellhop ray model is utilized to describe the process of sound propagation. The deep water waveguide environment is shown in Fig. 2.

The number of azimuths is N , and the vertical displacement of the rough seafloor at horizontal position r relative to the mean sea level is denoted as $H(r)$. The bottom is modeled as a semi-infinite homogeneous medium, where c_b , ρ_b , and α_b

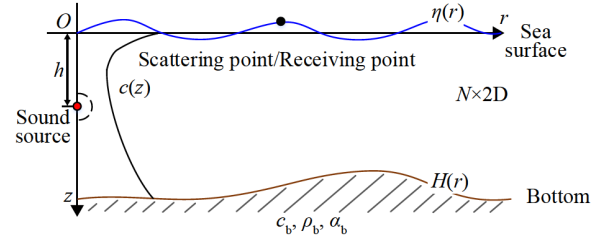


Fig. 2 Deep water waveguide environment.

represent the sound speed, density, and compressional wave attenuation of the sediment layer, respectively. The subscript “b” represents the bottom of sea. In deep water regions, silty-clay sediments are predominant; accordingly, these parameters are set to 1600 m/s, 1.8 g/cm³, and 0.1 dB/λ. Ray-tracing simulations are conducted for modeling and analysis based on the Munk sound speed profile. The source frequency is maintained at 1000 Hz with a source depth h of 1000 m, and the angular sector for ray calculation is specified as -90° – 90° .

3.1.2 Surface reverberation signal simulation results

Numerical simulations were performed to analyze the time-domain waveforms of sea-surface reverberation under a monostatic configuration. Both the omnidirectional transmitter and the receiver are positioned at a depth of 1000 m. To capture the acoustic field parameters, a horizontal line of 10001 virtual receivers is deployed at a depth of 5 m (near the sea surface), covering a range of 10 km with a spatial resolution of 1 m. This setup facilitates the acquisition of grazing angles, arrival times, and transmission losses (TL) for acoustic beams reaching the surface. When the receiver spacing is sufficiently dense, the propagation characteristics and energy levels of rays impinging upon different regions of a single scattering cell are assumed to be uniform. Under this assumption, the propagation state of a representative point can be utilized to characterize the entire scattering facet. The total intensity at any temporal instance is then derived by multiplying the response of each scattering element by its effective area and aggregating these contributions.

Due to the presence of multipath propagation, the acoustic trajectories from the source to the scatterer and from the scatterer back to the receiver are not necessarily reciprocal. Consequently, the incident transmission loss TL_i and the scattered transmission loss TL_s must be calculated independently. By incorporating these independent loss terms, Eq. (1) is reformulated as

$$RL = SL + S_s - TL_i - TL_s + 10\lg A - 2ra. \quad (17)$$

In this study, the SL is set to 0 dB to facilitate normalized reverberation intensity calculations. The parameter A represents the cumulative area of all contributing scattering elements at a specific temporal instance; under omnidirectional conditions, this is modeled as an annular region $A = \pi r c_w \tau$. The reverberation level is obtained from this

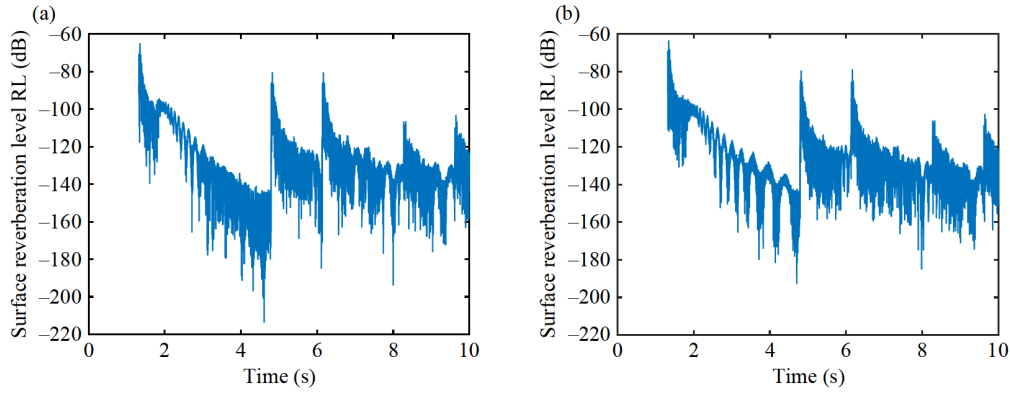


Fig. 3 Numerical simulation of sea-surface reverberation under flat surface conditions: (a) CW signal reverberation; (b) LFM signal reverberation.

formulation, and it is superimposed in the time domain to form a reverberation impulse signal. Subsequently, the time-domain waveform of the sea-surface reverberation is synthesized by convolving the impulse response with the transmitted signal. For simulation, the continuous wave (CW) pulse is set at 1000 Hz, while the linear frequency modulated (LFM) signal sweeps from 800 Hz to 1200 Hz. Additional parameters include a sampling frequency of 10 kHz, a pulse width of 5 ms, a recording duration of 10 s, and an ocean depth of 3600 m. The numerical simulation results for sea-surface reverberation under flat surface conditions for both signal types are illustrated in Fig. 3.

It can be seen that the reverberation time-domain waveform obtained by transmitting a linear frequency-modulated signal is clearer and has higher resolution than that obtained by transmitting a CW pulse signal. Among them, the reverberation level is expressed as the result after normalization, which is converted from the amplitude result calculated by Bellhop. Moreover, all the reverberation level calculations in this paper adopt the relative unit dB:

$$RL = 20 \lg A. \quad (18)$$

As shown in Fig. 3(a), the direct-scattering reverberation arrives first at 1.3 s, and it has the highest intensity and the fastest attenuation. Subsequently, it is the surface reverberation that has undergone only one bottom reflection. Since the bottom depth is greater than twice the source depth, that is, the sound source is closer to the sea surface, the path of the sound wave after bottom reflection is longer than that without bottom reflection. Then, for the same number of reflections, the more bottom reflections, the later the arrival time of the scattered echo. Therefore, the sea-surface reverberation with surface + bottom reflection and double-bottom reflection arrives last. Through the above analysis, it can be concluded that each additional total reflection, especially the reflection from the interface closer to the sound source, results in a later arrival of the reverberation, a smaller peak intensity, and a slower attenuation.

This paper mainly analyzes the reverberation intensity of the direct scattering path, with a focus on studying the laws of its intensity peak and time decay. To analyze the relationship between the signal frequency and the peak reverberation intensity, a CW signal is selected. The remaining simulation conditions are the same as above. Only the frequency range of 500–4000 Hz is selected, with a frequency interval of 100 Hz. The changes in the peak reverberation intensity at different frequencies are observed, as shown in Fig. 4. In a short period, the reverberation can be approximated as a time-invariant system. Especially for the propagation channel of direct scattering, the reverberation can be suppressed based on a filter under the time-invariant assumption.

In the frequency range from 500 Hz to 4000 Hz, the variation range of the peak intensity of reverberation is approximately 10 dB. Since the reverberation characteristics are affected by factors such as environmental parameters, sea-surface fluctuations, bottom characteristics, and receiver movement, they will change over time. Subsequently, by changing the simulation environment, it can be observed that there is no fixed correlation or obvious pattern among the propagation channels of different paths. Even for the same path, the peak intensity of reverberation also shows significant unpredictability.

3.2 Prediction of undulating sea surface waveform

3.2.1 Data preprocessing for wind waves and swell

The region bounded by latitudes from 5°N to 20°N and longitudes from 105°E to 120°E, where the sea depth exceeds 1000 m, was chosen as the statistical domain to analyze the relationships among wind speed, wind waves, and primary swell. As illustrated in Fig. 5, both primary swell and wind waves are strongly correlated with wind speed and increase as wind speed increases. When wind speed is below 8 m/s, the energy of the primary swell exceeds that of wind waves, indicating that the swell dominates the sea state.

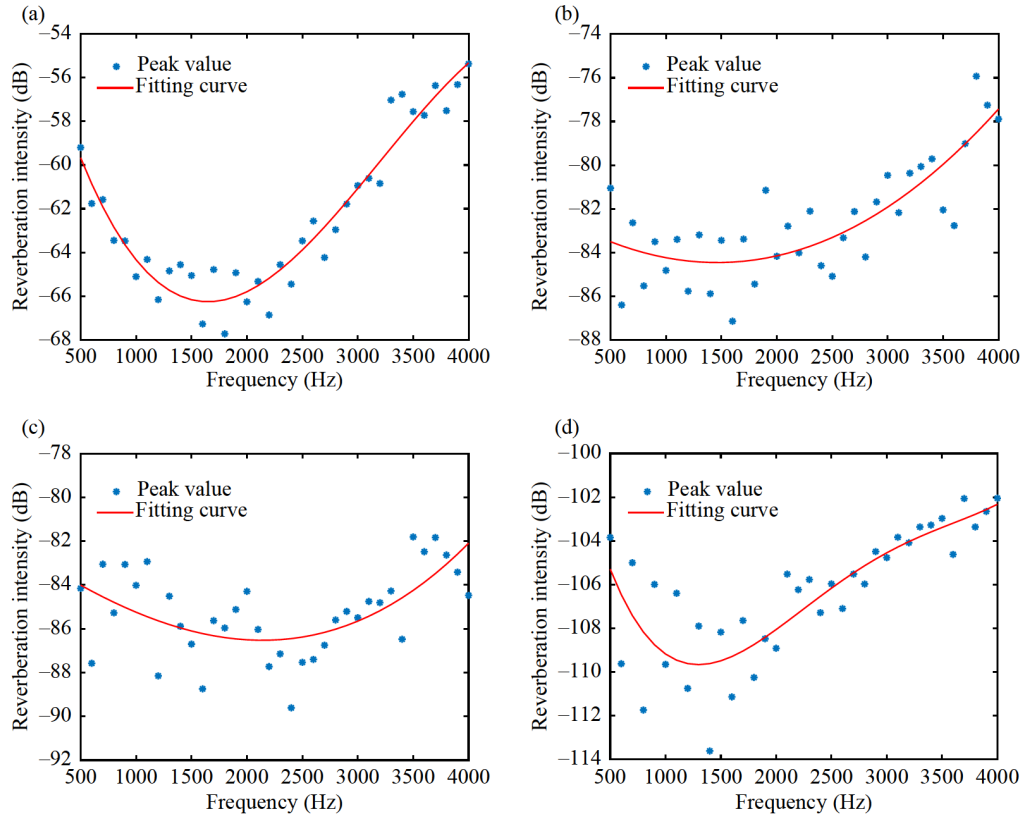


Fig. 4 Variation of sea surface reverberation peak with frequency: (a) Direct path reflection; (b) Once bottom reflection; (c) Once surface reflection + once bottom reflection; (d) Twice bottom reflection.

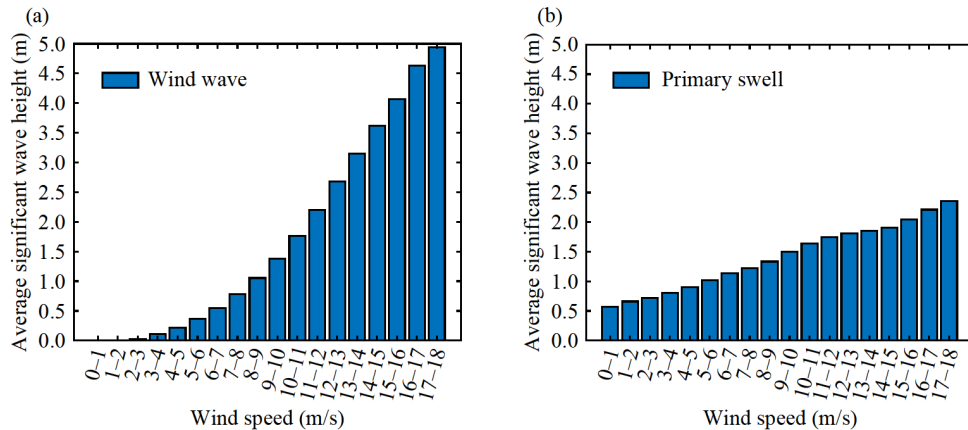


Fig. 5 Mean of significant wave heights of wind wave and primary swell at different wind speeds: (a) Wind wave; (b) Primary swell.

When wind speed exceeds 8 m/s, the significant wave height of wind waves increases significantly. As wind speeds typically range around 5 m/s, and conditions with wind speeds exceeding 18 m/s are infrequent in most parts of the study area, this paper primarily focuses on data with wind speeds up to 18 m/s. The wind speed, wind wave, and swell data used in this study were derived from the ERA5 reanalysis dataset, with hourly intervals, for the year 2022.

In the simulation of undulating sea surfaces, the total wave height is influenced not only by the heights of wind

waves and swell but also by the angular relationship between them. To reduce simulation errors, the directional differences between wind waves and main swell at different wind speeds were quantitatively analyzed, as shown in Fig. 6.

Wind waves are primarily driven by wind. As wind speed increases, wind waves gradually become dominant, and their direction becomes more aligned with the wind direction, causing the angular difference from the mean wave direction to decrease from approximately 35° to less than 5° . By contrast, swell waves are generated by distant winds or

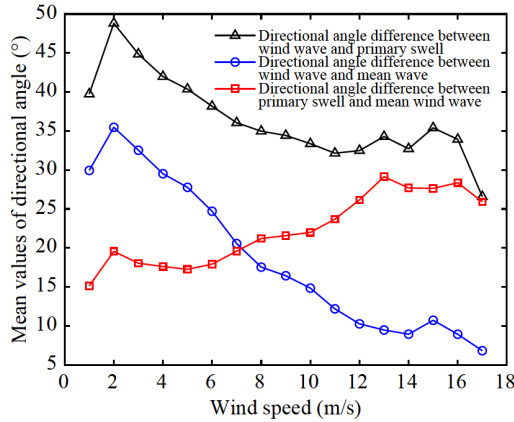


Fig. 6 Angular differences between wind waves, main swell, and waves at different wind speeds.

historical wind fields, and their propagation direction is less influenced by wind speed. The overall wave direction aligns more with the wind as wind speed increases, while the primary swell direction may remain mostly unchanged or vary slightly. This results in an increased angular difference between primary swell and mean wave direction. Considering the directional characteristics of wind waves and primary swell in the study area, the directional difference of the primary swell is assigned based on the statistical mean of the black triangles in Fig. 6 when simulating undulating sea surfaces at different wind speeds. This ensures that the simulation results more accurately reflect actual ocean conditions. The same method is applied to the input parameters for significant wave heights of both wind waves and primary swell.

3.2.2 Validation of the undulating sea surface model

This section validates the dual-peak spectrum model for undulating sea surfaces, including both wind waves and swell, by comparing the simulated significant wave heights at different wind speeds with ERA5 statistical data. To calculate the significant wave height, a $500 \text{ m} \times 500 \text{ m}$ simulation area was defined. Data from this area were collected at 10-s intervals. During a 15-min period, the 100 largest wave heights were recorded. After sorting, the average of the top 33 was taken as the significant wave height. The results of the comparison are presented in Fig. 7. At low to moderate wind speeds, the model slightly overestimates the statistical mean. In contrast, empirical estimates of the significant wave height of wind waves, excluding the contribution from swell, are significantly lower than the significant wave height of total waves. The overall increasing trend of the model's significant wave height with wind speed aligns well with the observed data. The model demonstrates particularly strong performance at high wind speeds, with a small mean absolute error.

The Beaufort wind scale was employed to describe and categorize sea surface conditions. The significant wave heights were statistically analyzed for each wind speed interval, as shown in Table 1. The simulated significant wave

height results exhibit a small mean absolute error compared to the observed data within the wind speed range of 18 m/s, demonstrating that the bimodal wave spectrum model for wind and swell waves exhibits high adaptability to surface roughness.

3.3 Analysis of surface reverberation

3.3.1 The non-directional surface reverberation intensity

In this section's simulation process, based on the positive correlation between sea surface undulation and wind speed, different sea states were generated by adjusting wind speed conditions. The significant wave heights of wind waves and swell, along with their angular separation parameters, were predicted using the deep-water ocean data described in the previous section. These predicted values served as standardized inputs. This approach effectively captures the characteristics of undulating sea surfaces under varying wind speeds. As a result, changes in wind speed

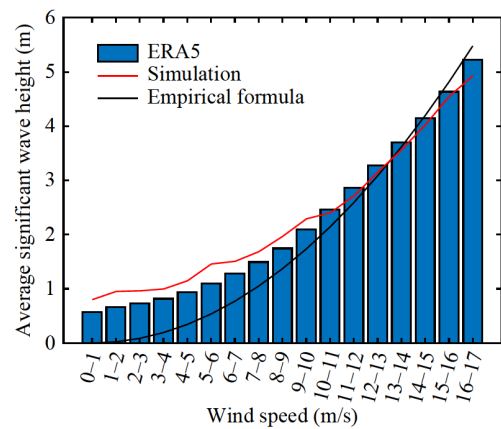


Fig. 7 Validation of simulated significant wave heights by the undulating sea surface model.

Table 1 Statistical and modeled mean values of significant wave height based on the Beaufort wind scale

Wind force	Wind speed (m/s)	Minimum	Mean	Maximum	Simulated mean
0 (Calm)	0–0.2	0	0.1573	3.6394	0.0065
1 (Light air)	0.3–1.5	0.0601	0.6431	5.8385	0.8826
2 (Light breeze)	1.6–3.3	0.0672	0.7313	6.2063	0.9074
3 (Gentle breeze)	3.4–5.4	0.1513	0.9279	6.5539	1.0291
4 (Moderate breeze)	5.5–7.9	0.2499	1.3204	7.1011	1.8798
5 (Fresh breeze)	8.0–10.7	0.5068	1.9889	7.0390	2.2087
6 (Strong breeze)	10.8–13.8	0.9484	3.0855	7.3940	3.0919
7 (Near gale)	13.9–17.1	1.9870	4.4245	8.1435	4.1030
8 (Gale)	17.2–20.7	3.1680	5.9073	8.3797	4.5201

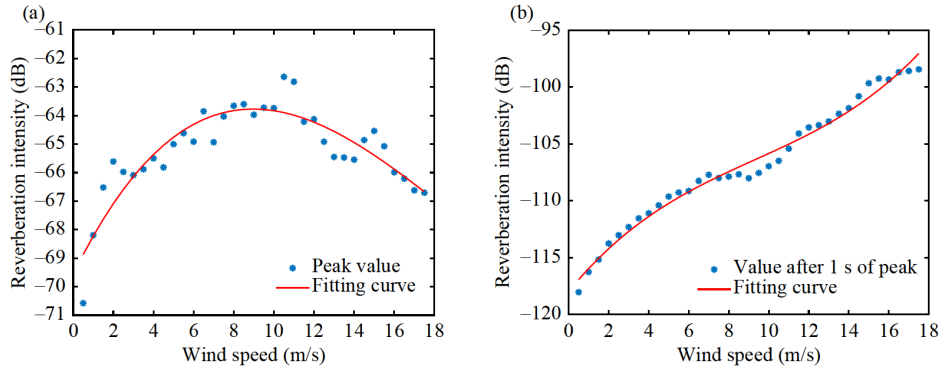


Fig. 8 Variation of reverberation peak and reverberation after 1-s decay with wind speed in an undulating sea surface: (a) Reverberation peak; (b) Reverberation after 1-s decay.

directly determine the input parameters for both the 1D numerical model of the undulating sea surface and the small-slope scattering model. Based on the principles of the small-slope scattering model, the influence of undulating sea waves on sea surface reverberation can be derived, enabling further analysis of its underlying mechanisms.

The influence of undulating sea surfaces due to wave action on sea surface reverberation was analyzed, focusing on two aspects: reverberation peak intensity and decay rate. The dynamic 3D undulating sea surface was divided into 8 directions and 10 time intervals. The signals from eight directions are superimposed and synthesized at the signal level for non-directional analysis. In addition, while keeping the same initial sea state conditions, modify the time and continuously obtain the heave data at an interval of 30.1 s. That is, repeat the experiment 10 times. The peak value of the reverberation signal $P_{1,i}$ as extracted for each of the ten realizations, and the mean peak value P_1 as calculated across the ten trials, $P_1 = (\sum_{i=1}^{10} P_{1,i}) / 10$, recorded as the reverb peak. In addition, for each of the ten realizations, the peak reverberation value $P_{2,j}$ within a 10-ms time window starting 1 s after signal decay was extracted. The mean of these attenuated reverberation peak values P_2 was then calculated across the ten realizations $P_2 = (\sum_{j=1}^{10} P_{2,j}) / 10$ and hereafter referred to as the 1-s delayed reverberation level. Finally, the simulation results showing the variations in reverberation peak intensity and reverberation value after 1-s decay with wind speed are presented in Fig. 8. The reverberation intensity is represented in relative units.

The reverberation peak intensity initially increases and then decreases with wind speed, reaching its maximum at approximately 10 m/s, followed by a gradual decline. In contrast, the reverberation decay rate $|P_2 - P_1|$ decreases monotonically as wind speed increases. Additionally, the significant inherent randomness of the initial ocean state may

cause reverberation intensities at similar wind speeds to exhibit fluctuations and errors. Fitting curves to the data can more clearly reveal the variation patterns of reverberation peak intensity and decay rate with wind speed.

3.3.2 Anisotropy of surface reverberation

Introducing an undulating sea surface environment, characterized by the combination of wind waves and swell, induces anisotropic properties in the direct-scattering sea surface reverberation. Specifically, the received reverberation intensity exhibits variations with azimuth and is influenced by the wind direction.

To distinguish between downwind and crosswind sea surface reverberation, it is necessary to perform multiple convolution calculations separately for each specific direction. Following the same computational approach as $N \times 2D$ method, the partitioned intervals are assigned to either the downwind or crosswind directions. Specifically, for a given wind direction on the undulating 3D sea surface, a sector spanning $\pm 15^\circ$ in both clockwise and counter-clockwise directions, corresponding to a total angular range of 30° , is defined. Undulating sea surface samples are collected within this sector at 5° intervals. The results from the seven sea surface samples are combined at the signal level and averaged over ten time segments. Finally, the variations in the reverberation peak and its decay after 1 s with wind speed under different wind directions are obtained, as shown in Fig. 9.

Considering 10 m/s as the threshold wind speed, the difference in reverberation intensity between the downwind and crosswind directions is negligible below this threshold, falling within the expected error range. When the wind speed exceeds the threshold, the sea surface waves become more coherent, forming a relatively regular wave structure. This coherence results in more consistent acoustic reflection from the sea surface, with energy becoming better synchronized both temporally and spatially, thereby increasing the peak reverberation intensity. This

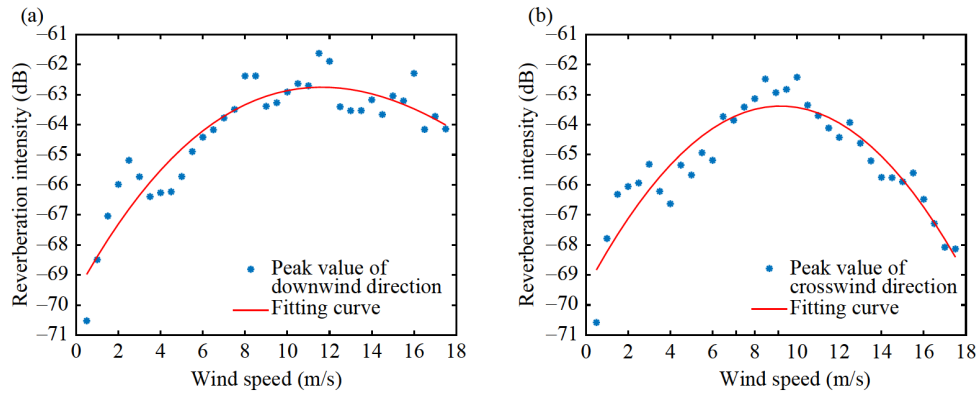


Fig. 9 Variation in the reverberation peak in response to wind speed in downwind and crosswind undulating sea surface environments: (a) Downwind; (b) Crosswind.

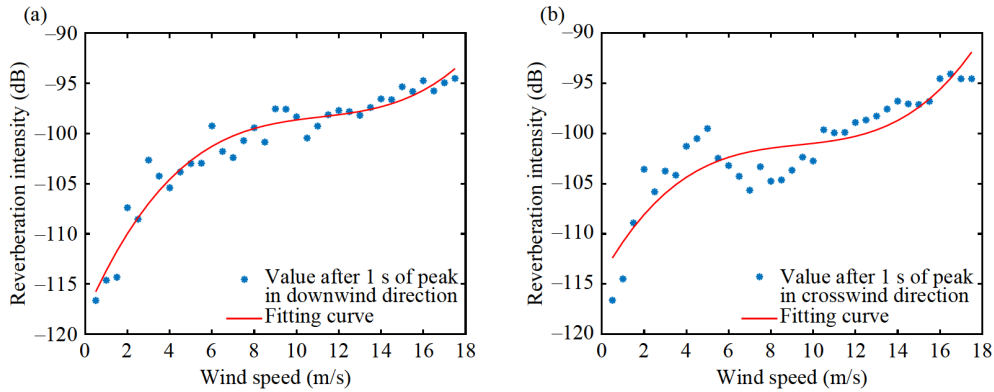


Fig. 10 Changes in the reverberation after 1-s decay as a function of wind speed under downwind and crosswind undulating sea surface conditions: (a) Downwind; (b) Crosswind.

enhancement is particularly pronounced in the downwind direction. A similar trend is observed in reverberation decay, as shown in Fig. 10. In comparison to Fig. 8, the reverberation intensity after 1 s of decay shows an overall increase of approximately 5 dB.

4 Conclusion

In this paper, a sea surface reverberation model under the condition of an undulating sea surface is first established. Aiming at the anisotropy of sea surface reverberation, the environmental variables of surface undulation are introduced, and a bimodal wave spectrum of wind waves and swell is constructed. Combined with the bimodal wave spectrum, a numerical simulation of 3D surface reverberation under undulation is realized. Then, the $N \times 2D$ method is used to calculate the surface reverberation intensity. The differences between the downwind direction and the crosswind direction are analyzed emphatically. The simulation results show that the sea surface undulation makes the sea surface reverberation start to fluctuate and causes a small

increase in the peak intensity. When the wind speed exceeds 10 m/s, due to the multi-path non-coherent superposition effect caused by the synchronous undulation of waves, the peak intensity of reverberation under the downwind and upwind conditions is significantly higher than that under the crosswind condition, which demonstrates the anisotropic characteristics of sea surface reverberation on the sea surface undulation.

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