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Vertically Moving Target Localization Based on Interference Feature Matching Using a Single Hydrophone

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Abstract: To address the performance degradation of traditional underwater target localization algorithms in high-speed motion scenarios, this paper proposes a vertically moving localization method based on interference feature matching using a single hydrophone. Due to the overlapping of interference fringes in the time–frequency domain, the method first employs a two-dimensional homomorphic filter to separate different types of interference fringes while removing line-spectrum interference. Then, a theoretical interference period database is constructed, and feature matching is performed on the interference fringes to achieve localization of the vertically moving target. Simulation results show that, under conditions of strong broadband noise and line-spectrum interference, the proposed method effectively separates and restores the interference fringes of high-speed vertically moving targets and successfully locates the moving target under large Doppler conditions. Further validation using field data from Qiandao Lake confirms that the actual measurements align with theoretical analysis, validating the effectiveness of the proposed method.

Keywords: interference structure; vertically moving target; multipath; underwater acoustics; localization



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1. Introduction

A vertically moving target is typically launched from a fixed depth on the seabed or within the water column and then moves at a relatively high velocity toward the sea surface. Traditional localization methods, such as MFP [1–3], TDOA [4–7], and DOA [8], experience significant performance degradation due to the decline in signal stationarity and multipath effects. In contrast, interference fringes contain critical information about the target’s position and motion status, which can be used for localization.

Broadband continuous-spectrum noise generated by an underwater moving target, primarily due to propeller cavitation, is impacted by waveguide boundaries. These boundaries lead to the overlapping of multipath signals, which in turn causes interference phenomena. Consequently, interference structures appear in the time–frequency domain of the received signals. As these interference structures contain crucial information about the target’s velocity, position, and the characteristics of the underwater acoustic channel, extracting parameters from the trajectories of the interference fringes proves useful for inferring the target’s movement and the underwater environment’s attributes. The key challenge in localization is obtaining clear, distinct fringes and accurately identifying the fringe peaks (i.e., the centerlines of the fringes), from which relevant features can be extracted.

The observation and theoretical study of underwater acoustic interference phenomena began in the 1950s and 1960s. Wood [9] conducted tank experiments on the propagation of continuous single-frequency signals, discovering spatial interference structures under iso-speed conditions. This laid the groundwork for further analysis and application of these interference structures. Subsequent studies focused on the waveguide invariant and the influence of factors such as the underwater environment, receiver position, and seabed sediment distribution on the interference structures [10–12]. Quijano et al. [13] explored interference characteristics of echo sound fields from active sonar signals produced by explosive sources and found similar interference patterns, analyzing the slopes of these fringes. Zhao et al. [14] extended this work to moving targets, investigating the time–frequency domain for interference fringes and clarifying how variables like target and receiver positions, the underwater environment, and target velocity influence the visibility of interference structures. Ehrhardt et al. [15] analyzed the characteristics of focal point coordinates on the holograms of targets moving in different directions, which are used to determine the motion state of the targets.

In the following years, numerous practical applications of interference structures were explored. Heaney et al. [16] used normalized slopes and extended-time parameters in the range–frequency domain for horizontally moving targets to classify and invert the physical properties of sediment layers. They later expanded this approach to range-dependent underwater environments. Sostrand et al. [17] and Turgut et al. [18] combined waveguide invariant and equivalent depth concepts, employing time–frequency interference structures to track and measure multiple targets. An et al. [19] used differences in interference fringe slopes for surface and submerged targets in waveguides with negative thermoclines to distinguish between them without needing prior knowledge of range or underwater conditions. Yu et al. [20] proposed a passive ranging method based on the waveguide invariant using dual elements, removing the need for the closest point of approach and broadening the applicability of fringe-based localization. Ren et al. [21] utilized an extended Kalman filter and interference fringe characteristics to estimate the range of moving ships efficiently, bypassing the need for environmental data. Zhao et al. [22,23] demonstrated that extracting trajectory parameters of interference fringes from direct and surface-reflected signals enabled the effective localization of vertically moving targets and employed matching methods in the time–frequency domain for tracking three-dimensional linear motion targets. Pereselkov et al. [24] estimated the range, speed, and motion direction of surface targets using the focal spot coordinates on the holograms of interference fringes.

However, interference structures are affected by factors like the signal-to-noise ratio (SNR), multiplicative noise, and interference from other targets. These factors can cause the interference fringes to be corrupted or unclear, making direct application difficult without preprocessing. Yang et al. [25] utilized conventional beamforming on a horizontal line array to enhance array gain and obtain clearer fringes compared to a single element. Gall et al. [26] exploited the fact that interference structures corresponding to ships moving in different directions occupy distinct regions in the two-dimensional Fourier transform (hologram) domain, helping to isolate target-specific fringes, although multiplicative noise remains a challenge. Kim et al. [27] proposed coherently combining Green’s functions at adjacent time instances to improve the estimation of Green’s functions, boosting their SNR and enhancing fringe clarity without prior knowledge of range or sound speed profile (SSP). Pereselkov et al. [28] analyzed interference structure energy distribution in the hologram under internal wave conditions and reconstructed the interference patterns by filtering the corresponding holograms. Li et al. [29] used a large-aperture horizontal line array and wavenumber filtering to isolate surface-reflected–bottom-reflected (SRBR) modes, reconstructing the interference structures of each target. This method improved the separation

of interference fringes in multi-target scenarios but could not completely eliminate the multiplicative noise from the targets. Kuz'kin et al. [30] effectively extracted interference fringes from multiple targets of varying intensities by isolating different focal spots in cut-off holograms.

Interference fringes generated by various multipath signals provide essential information regarding the position and motion of a target, which can be utilized for localization purposes. Consequently, this paper proposes a method for localizing a vertically moving target based on interference feature matching, using a single hydrophone. The interference structures in the direct-arrival zone of the sound field are influenced by several factors: (1) the high-energy radiated noise, causing the overlapping of multiple interference fringes in the spectrogram; (2) the presence of strong line-spectrum signals and the comparatively lower energy of broadband signals; (3) the disappearance of interference fringe peaks due to the target's radiated noise; and (4) as the target's vertical velocity increases, coherence among the multipath signals weakens, leading to the gradual disappearance of the interference fringes. These challenges impede the practical use of interference structures' features. To address them, this paper applies two-dimensional homomorphic filtering to separate different types of interference fringes, eliminate line-spectrum signals, and reduce the impact of radiated noise, thereby restoring the fringe peaks. Additionally, Doppler compensation is used to restore coherence between the multipath signals, further improving the visibility of the interference fringes. Finally, localization is achieved by matching the features of the interference fringes. Simulation experiments and lake trial data analysis confirm the effectiveness of the proposed methods.

The rest of this paper is organized as follows: Section 2 derives the model of interference structures in shallow water and introduces the method for separating and enhancing interference fringes using two-dimensional homomorphic filtering. Section 3 presents the method for vertically moving target localization based on interference feature matching. Section 4 provides a simulation analysis under conditions of high-speed motion and the presence of line-spectra. Section 5 discusses the processing of trial data from Qiandao Lake, validating the effectiveness of the proposed method. Section 6 concludes this research.

2. Enhancement of Interference Fringes Based on Two-Dimensional Homomorphic Filtering

2.1. Modeling of Interference Structures in Shallow Water

In shallow water, the ray theory is an approximate solution for underwater acoustic fields, owing to its simple mathematical form and clear physical interpretation. It applies to $f > 10c/H$, where f is the frequency, c is the sound speed in water, and H is the water depth. For water depth exceeding 50 m and signals in the 300~5000 Hz band, the conditions for using the ray theory are suitable. Consequently, ray theory can be employed to characterize the acoustic field of a vertically moving target, providing an intuitive description of the interference structure.

In the ray theory, the side view of the configuration with a vertically moving target and hydrophone is shown in Figure 1. In this paper, the direct signal is denoted as D , the surface-reflected signal is denoted as S , and the bottom-reflected signal is denoted as B .

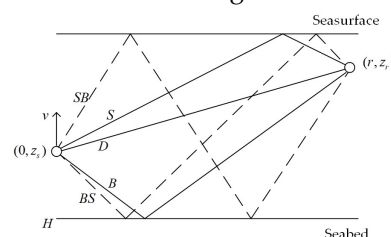


Figure 1. Side view of the configuration with a vertically moving target and hydrophone.

In an ideal iso-speed underwater waveguide, the impulse response of the sparse time-varying acoustic channel is generally modeled as the sum of multiple time-varying impulse responses [31]; that is,

$$h(t) = \sum_{m=1}^N \alpha_m(t) \delta((1 + \eta_m(t))(t - \tau_m(t))). \quad (1)$$

- $\alpha_m(t)$: the amplitude of the m -th multipath signal at time t ;
- $\eta_m(t)$: the Doppler coefficient of the m -th multipath signal at time t ;
- $\tau_m(t)$: the time delay of the m -th multipath signal at time t ;
- $\delta(t)$: the impulse response of underwater channels;
- N : the number of multipath signals.

Due to the attenuation caused by reflections on signal amplitude, this paper primarily investigates the effects of the direct signal, surface-reflected signal, and bottom-reflected signal. Consequently, in this paper, N is set to 3. The Doppler coefficient can be expressed as

$$\eta_m(t) = \frac{v}{c} \cos \theta_m(t). \quad (2)$$

- v : the velocity of the target;
- c : the underwater sound speed;
- $\theta_m(t)$: the emission angle of the m -th multipath signal at time t .

Let the target's motion direction be defined as 0° and the direction towards the receiver as positive. The broadband radiated noise emitted by the target is denoted by $s(t)$. The received signal $r(t)$ is the convolution of $s(t)$ with the underwater channel $h(t)$, which can be expressed as

$$r(t) = s(t) * h(t) = \sum_m \alpha_m(t) s((1 + \eta_m(t))(t - \tau_m(t))). \quad (3)$$

The motion of the target reduces the stationarity of the received signal. To address this, the signal is segmented into multiple frames of duration T . The length of each time window should be kept as small as possible to ensure the multipath components within each time window remain stationary. Owing to this short window length, it is assumed that, within each time window, the signal amplitude, Doppler coefficient, and time delay remain constant; that is, $\alpha_m(t) \approx \alpha_{m,t}$, $\eta_m(t) \approx \eta_{m,t}$ and, $\tau_m(t) \approx \tau_{m,t}$, respectively. Taking the Fourier transform yields the spectrum,

$$R(t, f) = \mathcal{F}[r(t)] = \sum_m \frac{\alpha_{m,t}}{1 + \eta_{m,t}} S(t, \frac{f}{1 + \eta_{m,t}}) e^{-j2\pi f \tau_{m,t}}. \quad (4)$$

- $S(t, f/\eta_{m,t})$: the spectrum of the m -th multipath signal at time t .

Then, the spectrogram of the received signal can be expressed as

$$I(t, f) = R(t, f) R^*(t, f) = \sum_m P_{mm}(t, f) + \sum_{m, m \neq n} \text{Re}[P_{mn}(t, f)] \cos(2\pi f \tau_{mn}(t)) - \sum_{m, m \neq n} \text{Im}[P_{mn}(t, f)] \sin(2\pi f \tau_{mn}(t)). \quad (5)$$

- $\tau_{mn}(t) = \tau_n(t) - \tau_m(t)$: the time delay difference between any two multipath signals.

$\text{Re}[\bullet]$ represents the real part, and $\text{Im}[\bullet]$ represents the imaginary part. $P_{mm}(t, f)$ represents the auto-power spectrum of the multipath signals, and $P_{mn}(t, f)$ represents

the cross-power spectrum among multipath signals. The expressions for $P_{mm}(t, f)$ and $P_{mn}(t, f)$ can be, respectively, expressed as

$$P_{mm}(t, f) = \left(\frac{\alpha_{m,t}}{1 + \eta_{m,t}} S\left(t, \frac{f}{1 + \eta_{m,t}}\right) \right)^2, \quad (6)$$

$$P_{mn}(t, f) = \frac{\alpha_{m,t}\alpha_{n,t}}{(1 + \eta_{m,t})(1 + \eta_{n,t})} S\left(t, \frac{f}{1 + \eta_{m,t}}\right) S^*\left(t, \frac{f}{1 + \eta_{n,t}}\right). \quad (7)$$

Equation (5) can be divided into three parts:

1. The first term, $\sum_m P_{mm}(t, f)$, is the superposition of the auto-power spectra of each multipath signal, which appears as the background in the time–frequency domain.
2. The second term, $\text{Re}[P_{mn}(t, f)]$, involves the active component of the cross-power spectra. The periodic function, $\cos(2\pi f \tau_{mn}(t))$, indicates the presence of periodic components in $I(t, f)$, both reflecting the coherence of the acoustic field in the time–frequency domain.
3. The third term, $\text{Im}[P_{mn}(t, f)]$, represents the reactive component of the cross-power spectra among the multipath signals. It contains the Doppler phase difference information between these signals.

Based on the above analysis, the interference structures are influenced by three major factors:

1. When the energy of some multipath signals is relatively low, the interference fringes exhibit lower energy. After superimposing with other higher-energy interference fringes, the overall clarity of the fringes deteriorates.
2. Because $\text{Re}[P_{mn}(t, f)]$ and the periodic function $\cos(2\pi f \tau_{mn}(t))$ have a multiplicative relationship, $\cos(2\pi f \tau_{mn}(t))$ is modulated by $\text{Re}[P_{mn}(t, f)]$, causing the peaks of the interference fringes to disappear.
3. Under high target speeds, the Doppler coefficient differences among multipath signals become significant, which increases $\text{Im}[P_{mn}(t, f)]$ and reduces coherence between the multipath signals, ultimately leading to the disappearance of the fringes.

2.2. Enhancement of Interference Fringes

From Equation (5), under the assumption of small Doppler shifts (i.e., $\eta \rightarrow 0$), the spectrogram between the multipath signals can be expressed as

$$I_{mn}(t, f) = |S(t, f)|^2 |H_{mn}(t, f)|^2. \quad (8)$$

Here,

$$|H_{mn}(t, f)|^2 = \alpha_{m,t}^2 + \alpha_{n,t}^2 + 2\alpha_{m,t}\alpha_{n,t} \cos(2\pi f \tau_{mn}(t)). \quad (9)$$

Equation (9) represents the power spectral density of the channel response. Since $|H_{mn}(t, f)|^2$ contains the position and motion information of the target, obtaining a clear representation of $|H_{mn}(t, f)|^2$ is a prerequisite for extracting interference fringe parameters.

Figure 2 illustrates the interference structures computed from Equation (9) under the condition that the target power spectrum $|S(t, f)|^2$ does not interfere with the signal. Specifically, Figure 2a shows the interference fringes between the direct and the surface-reflected signals, labeled IF_{SD} (interference fringes between the surface-reflected and direct signal), while Figure 2b displays the interference fringes between the direct and the bottom-reflected signals, labeled IF_{BD} (interference fringes between the bottom-reflected and direct signal). These two fringes are symmetric with respect to the time axis. When the target signal is not considered, the fringe peaks (centerlines) appear relatively clear. In contrast, Figure 3 presents the interference fringes observed in actual received signals, illustrating

that the broadband target signal modulates the fringes, causing the fringe peaks (i.e., the centerlines) to disappear. This effect becomes particularly apparent when the interference fringes are densely packed, further reducing their clarity. Therefore, it is necessary to restore the fringe peaks, effectively removing the influence of $|S(t, f)|^2$ on $|H_{mn}(t, f)|^2$. Because they are related through a multiplicative process, linear filtering alone cannot be used to remove this interference. Given the spectral differences between $|S(t, f)|^2$ and $|H_{mn}(t, f)|^2$, a two-dimensional homomorphic filtering approach was adopted to recover the fringe peaks.

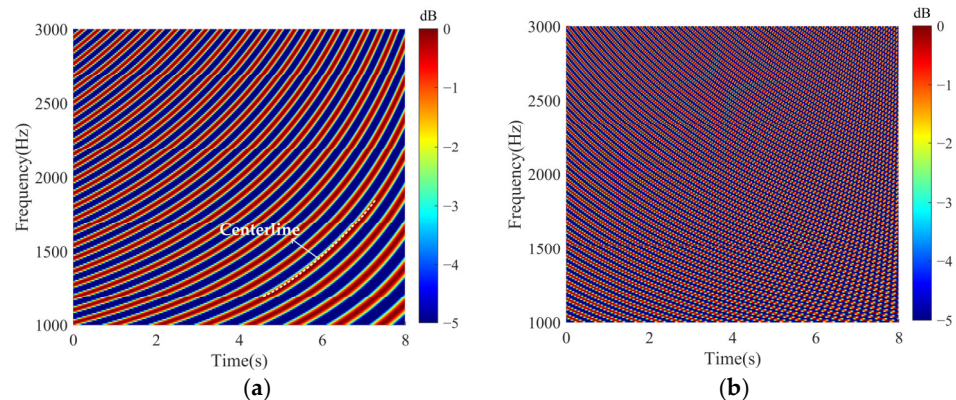


Figure 2. Interference fringes under the condition of not considering $|S(t, f)|^2$: (a) IFSD; (b) IFBD.

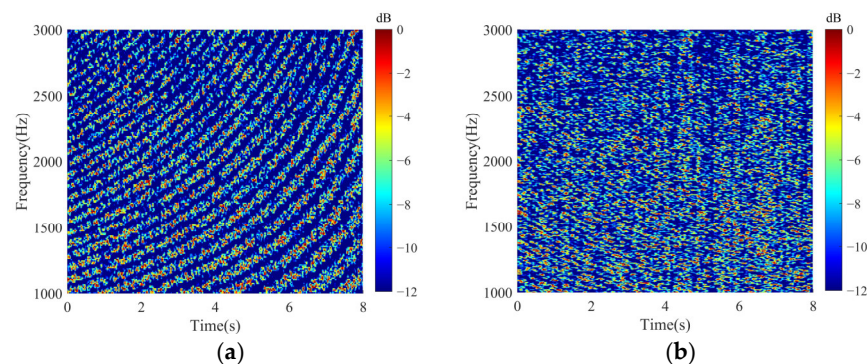


Figure 3. The interference fringes of the actual received signals: (a) IFSD; (b) IFBD.

To facilitate comparison, slices at $t = 6$ s from Figures 2a and 3a were taken, and the comparative results are displayed in Figure 4. This figure reveals that, theoretically, interference fringes should exhibit distinct peaks without multiplicative noise. However, the actual interference fringes show the peaks disappearing, indicating a loss of the centerlines of the fringes. Therefore, there is a need to restore the centerlines of these interference fringes.

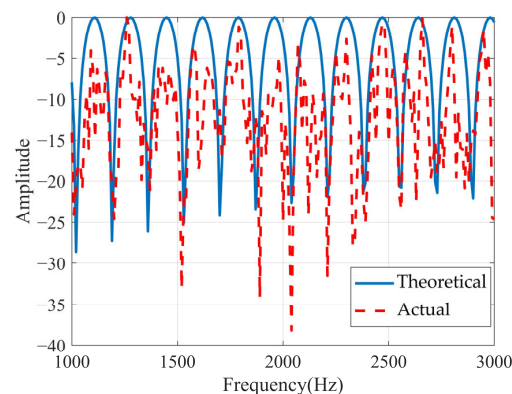


Figure 4. Slices at $t = 6$ s from Figures 2a and 3a.

Homomorphic filtering uses mathematical transformations to convert a nonlinear (multiplicative) combination of signals into a linear (additive) combination, thus simplifying the signal-processing procedure and facilitating noise removal and suppression. Typically, a logarithmic transform is applied to convert multiplicative noise into additive noise, making subsequent operations more intuitive and easier to implement. This technique has proven highly effective for signal and image enhancement and restoration.

As shown in Figure 5, the flowchart of two-dimensional homomorphic filtering involves the following key steps:

1. Apply a log transform to convert the multiplicative signal into an additive signal;
2. Use a linear two-dimensional filter to remove high-frequency components of the additive signal while preserving the low-frequency periodic components;
3. Convert the filtered signal back to its original multiplicative form via an exponential transform.

Through this process, the broadband noise of the target is effectively removed from the interference fringes, thereby restoring the fringe peaks.

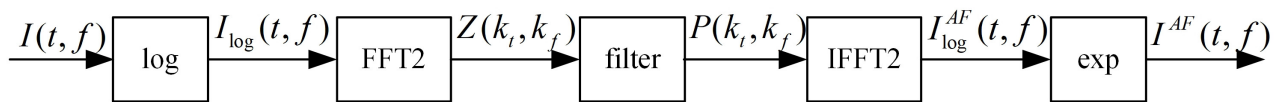


Figure 5. Flowchart of two-dimensional homomorphic filtering.

Taking the logarithm on both sides of Equation (8) yields the logarithmic spectrogram of the received signal,

$$I_{\log,mn}(t, f) = 2 \ln|S(t, f)| + 2 \ln|H_{mn}(t, f)|. \quad (10)$$

Through the two-dimensional homomorphic filtering algorithm, multiplicative signals in the spectrogram were transformed into additive signals. In Equation (10), the first term corresponds to the cross-power spectra of the multipath signals, which have a relatively wide bandwidth and span both the low- and high-frequency regions. The second term of Equation (10) represents the coherent periodic component, modeled as a slowly varying single-frequency function at low frequency. Compared to the second term, the first term exhibits higher energy content in the mid- and high-frequency ranges, whereas the second term is more prominent in the low-frequency region. By performing a two-dimensional Fourier transform on $I_{\log,mn}(t, f)$, one obtains the $Z(k_t, k_f)$ parameter domain. Here, k_t and k_f are defined as the image wavenumbers of $I_{\log,mn}(t, f)$. Within the (k_t, k_f) domain, $\ln|H_{mn}(t, f)|$ primarily maps to the low-frequency region, whereas $\ln|S(t, f)|$ spans the entire parameter plane. Consequently, to recover a cleaner version of $\ln|H_{mn}(t, f)|$, one can apply a low-pass filter to Equation (10), followed by an exponential transform on the filter's output. This results in the homomorphically filtered spectrogram,

$$I_{o,mn}(t, f) = \exp \left[L_{PF} \left(I_{\log,mn}(t, f) \right) \right]. \quad (11)$$

- $L_{PF}[\bullet]$: low-pass filtering.

Reference [14] presents the trajectory equations of IF_{SD} and IF_{BD} in an iso-speed underwater waveguide, which are, respectively, as follows:

$$f_{k,SD}(t) \approx \frac{2k-1}{4z_r} c \sqrt{1 + \frac{r^2 + z_r^2}{(z_{s0} - vt)^2}}, k = 1, 2, 3 \dots, \quad (12)$$

$$f_{k,BD}(t) \approx \frac{k}{2(H-z_r)} c \sqrt{1 + \frac{r^2 + (H-z_r)^2}{(H-z_{s0} + vt)^2}}, k = 1, 2, 3 \dots \quad (13)$$

- k : the serial number of the interference fringes.

It can be easily obtained from Equations (12) and (13) that

$$\frac{\partial f_{k,SD}}{\partial t} > 0, \frac{\partial f_{k,BD}}{\partial t} < 0. \quad (14)$$

It follows that the logarithmic spectrogram corresponding to IF_{SD} and IF_{BD} occupy different quadrants in the (k_t, k_f) parameter domain (specifically, IF_{SD} in quadrants II and IV, and IF_{BD} in quadrants I and III). Taking the logarithm of the signals in Figure 2 to obtain the logarithmic spectrogram and then performing a two-dimensional Fourier transform yields Figure 6, which displays the (k_t, k_f) -domain representations of IF_{SD} and IF_{BD} . The presence of harmonics results in the formation of different regions with progressively amplitudes in the (k_t, k_f) -domain. Clearly, for a vertically moving target, these two types of interference fringes can be readily separated based on the quadrant in the (k_t, k_f) -domain. Hence, when performing homomorphic filtering on the spectrogram, setting a low-pass filter to select only quadrants I and III of the (k_t, k_f) -domain yields the homomorphically filtered IF_{BD} ; selecting quadrants II and IV similarly yields the homomorphically filtered IF_{SD} .

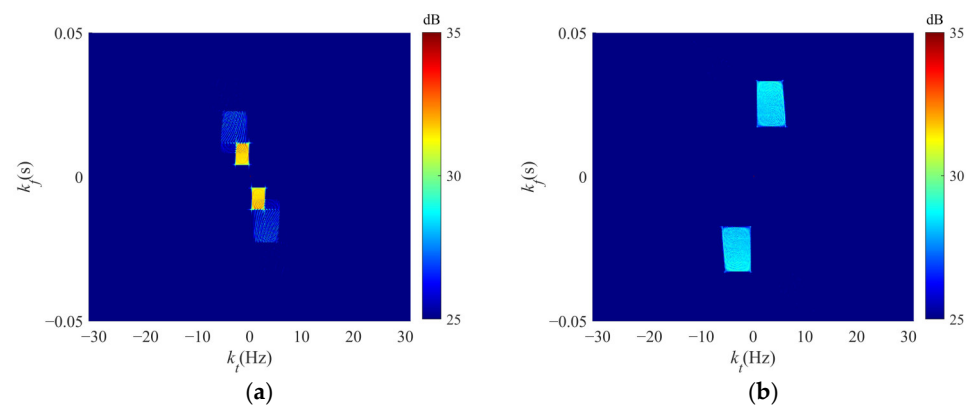


Figure 6. The (k_t, k_f) domain of the logarithmic power spectrum under the condition of not considering $|S(t, f)|^2$: (a) The (k_t, k_f) domain of IF_{SD} ; (b) The (k_t, k_f) domain of IF_{BD} .

After homomorphic filtering, the multiplicative term $|S(t, f)|^2$ that modulates the spectrogram was removed, leaving behind only $H_{mn}(t, f)$. The peaks of $H_{mn}(t, f)$ correspond to the centerlines of the interference fringes, thus restoring the interference characteristic of the fringes.

In the aforementioned study, the primary focus was on low-speed moving targets. However, when the target undergoes high-speed vertical motion, the Doppler coefficient differences among the multipath signals become large, leading to reduced coherence and a gradual disappearance of the interference fringes with increasing target speed. These Doppler differences, specifically η_{SD} between the surface-reflected and the direct signal, and η_{BD} between the bottom-reflected and the direct signal, can be estimated using a broadband ambiguity function. By taking advantage of the sign difference between η_{SD} and η_{BD} for a vertically moving target, one can search for peaks in different quadrants of the ambiguity function to determine the values of η_{SD} and η_{BD} . Subsequently, Doppler compensation was applied separately to the surface-reflected and bottom-reflected signals, thereby realigning them with the direct signal and restoring coherence. Finally, two-dimensional homomorphic filtering was performed to enhance the recovered interference fringes.

3. Vertically Moving Target Localization Based on Interference Feature Matching

Based on the calculations from Section 2, the theoretical interference period of IF_{BD} , Δf_{BD} , and IF_{SD} , Δf_{SD} , at each time, can be obtained. The channel response between different test points (r, z_s) and the hydrophone was calculated using Bellhop, and the theoretical interference periods, Δf_{BD}^{COPY} and Δf_{SD}^{COPY} , at each time, were computed from Equation (9). The cost function maximization problem is constructed as follows:

$$C_{SD}(r, z_s) = \frac{1}{|\Delta f_{SD} - \Delta f_{SD}^{COPY}|}. \quad (15)$$

$$C_{BD}(r, z_s) = \frac{1}{|\Delta f_{BD} - \Delta f_{BD}^{COPY}|}. \quad (16)$$

By combining the two ambiguity functions, the total cost function is obtained:

$$C(r, z_s) = C_{SD}(r, z_s)C_{BD}(r, z_s). \quad (17)$$

Then, the maximum value of the ambiguity function was searched, and its position was used as the estimated location of the target.

In summary, the interference fringe enhancement technique proposed in this paper can be outlined in the following steps:

1. If the interference fringes are blurred or have disappeared because of high-speed target motion, methods such as the wideband ambiguity function can be employed to estimate the Doppler coefficients among the multipath signals. The surface-reflected and bottom-reflected signals are then individually compensated for Doppler effects, thereby restoring clear interference fringes. In scenarios where the target motion is low speed, proceed directly to Step 2;
2. Obtain the spectrogram of the received signal via STFT, and, then, apply a logarithmic transform to obtain the logarithmic spectrogram;
3. Perform a two-dimensional Fourier transform on the logarithmic spectrogram to obtain the (k_t, k_f) domain;
4. In the (k_t, k_f) domain, IF_{SD} maps primarily to quadrants II and IV, whereas IF_{BD} maps primarily to quadrants I and III. According to the energy distribution in the (k_t, k_f) domain, design and apply separate two-dimensional low-pass filters for these quadrants;
5. Perform an exponential transform on the filtered outputs to obtain the separated IF_{SD} and IF_{BD} .
6. The interference periods for both IF_{SD} and IF_{BD} are calculated, and the theoretical interference periods are obtained through Bellhop. The depth-range ambiguity function is then calculated through feature matching, and peak search is applied to determine the target's position.

4. Simulation

This section investigates the enhancement of interference fringes when the target moves vertically at a high speed, leading to large Doppler differences among multipath signals. The simulation conditions are as follows: The schematic diagram in the simulation is shown in Figure 7. The bottom sediment has a sound speed of 1677 m/s and a density of 1.83 g/cm³. The target travels vertically upward from 80 m to 20 m depth at a speed of 90 knots. The hydrophone is placed at a range of 300 m and a depth of 40 m. The analysis covers 1000–3000 Hz. To ensure signal stationarity within the time window

while maintaining a sufficient number of points in the spectrogram, a 0.1 s time window was selected.

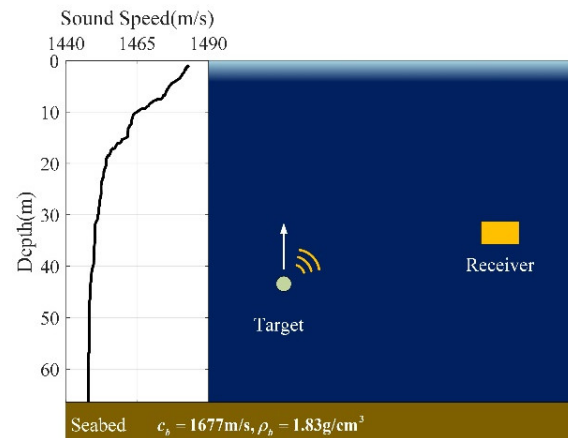


Figure 7. Schematic diagram in the simulation.

Figure 8 depicts the spectrogram of the received signal and its corresponding (k_t, k_f) domain. Because the target is moving at a high speed, the Doppler coefficient differences among the multipath signals are large, causing all interference fringes to vanish. In the (k_t, k_f) domain, there are no areas in the low-frequency range that correspond to the interference fringes.

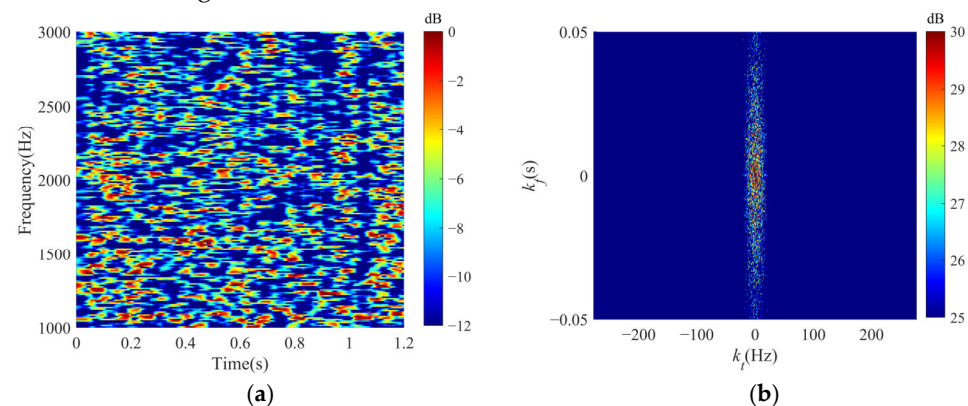


Figure 8. The spectrogram of the received signal and its corresponding (k_t, k_f) domain: (a) The spectrogram. (b) The (k_t, k_f) domain.

First, the Doppler coefficient differences between the direct and the bottom-reflected signal, as well as between the direct and the surface-reflected signal, are estimated. Based on these estimates, Doppler compensation is separately applied to the received signals. Figure 9 shows the spectrogram after Doppler compensation. As can be seen, once Doppler compensation is performed, the coherence among the multipath signals is restored, leading to the recovery of both IF_{BD} and IF_{SD} . However, the interference fringes remained relatively indistinct.

Next, the Doppler-compensated spectrogram is transformed via a logarithm and then subjected to a two-dimensional Fourier transform, yielding the (k_t, k_f) domain shown in Figure 10. In the (k_t, k_f) domain, IF_{BD} maps primarily to the low-frequency regions of quadrants I and III, whereas IF_{SD} maps to the low-frequency regions of quadrants II and IV.

A two-dimensional low-pass filter is then designed, whose passband corresponds to the white box indicated in Figure 10. Figure 11 shows the output of the homomorphic filtering process. For comparison, Figure 12 presents the theoretical interference fringes calculated using Bellhop. By comparing these figures, one can see that the peaks (center-

lines) of IF_{BD} and IF_{SD} are both successfully recovered, and the recovered fringe trajectories match the theoretical trajectories.

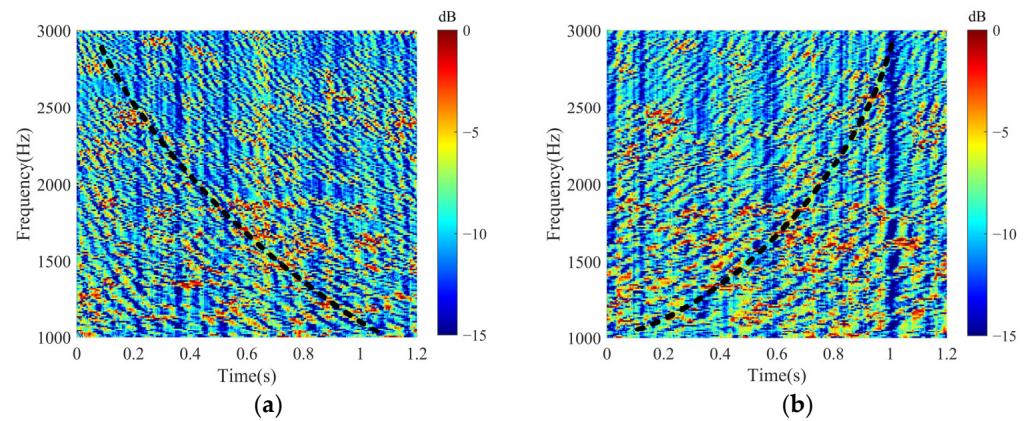


Figure 9. The spectrogram after Doppler compensation. Black dashed lines represent the theoretical trajectories of interference fringes: (a) Doppler compensation on the bottom-reflected signal. (b) Doppler compensation on the surface-reflected signal.

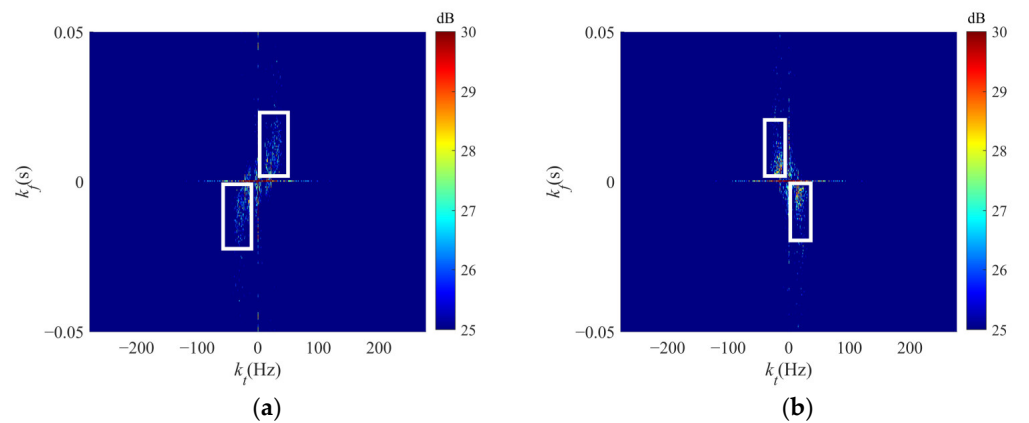


Figure 10. The (k_t, k_f) domain of the spectrogram after Doppler compensation. Here, white boxes represent two-dimensional low-pass filters: (a) The (k_t, k_f) domain corresponding to IF_{BD} ; (b) The (k_t, k_f) domain corresponding to IF_{SD} .

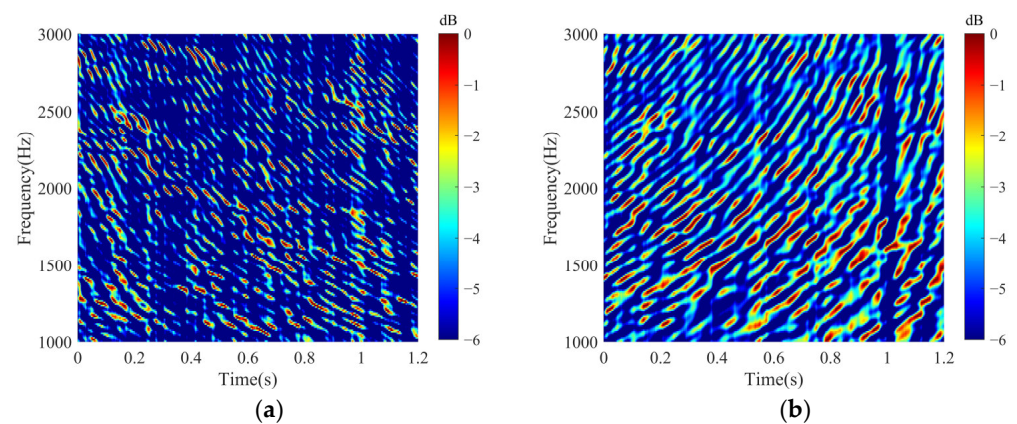


Figure 11. The spectrogram after two-dimensional homomorphic filtering: (a) IF_{BD} ; (b) IF_{SD} .

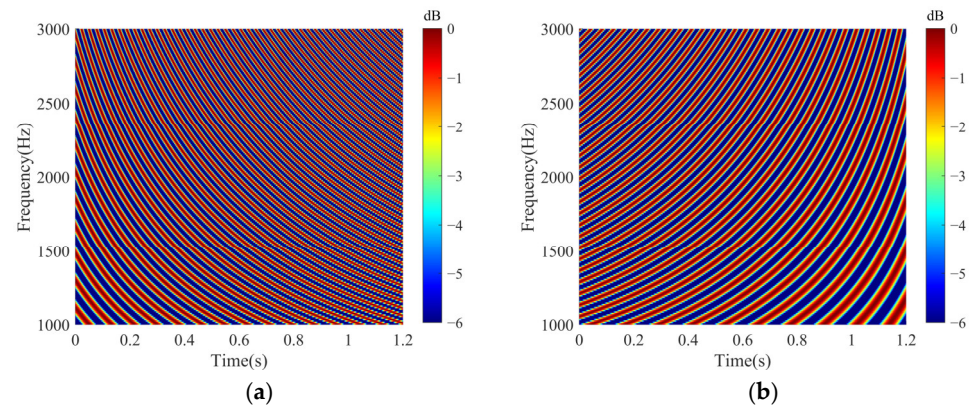


Figure 12. Theoretical interference fringes: (a) IF_{BD}; (b) IF_{SD}.

To further quantify the recovery effect of the interference fringes, we employ the concept of power spectral entropy. A two-dimensional power spectral entropy cost function is defined as

$$h = -\sum_{k_t} \sum_{k_f} Z(k_t, k_f) \log_2 Z(k_t, k_f) \Delta k_f \quad (18)$$

where $Z(k_t, k_f)$ is the two-dimensional Fourier transform of the logarithmic spectrogram in the (k_t, k_f) domain, and Δk_f is the resolution along the k_f axis. Power spectral entropy is defined as the entropy of a signal's power spectral density, which is often used to describe how uniformly a signal's energy is distributed across its frequency range. When a signal covers a wider bandwidth, its power spectral entropy is higher, indicating a more even distribution of energy among frequency bands. Conversely, when a signal's energy is concentrated in a specific band, the power spectral entropy is lower, reflecting a more localized frequency distribution. For interference fringes in a spectrogram, if the fringes are unaffected by the target's broadband radiated noise, they essentially consist of single-frequency periodic components, resulting in lower power spectral entropy. However, when the fringes are influenced by broadband noise, their frequency components broaden, leading to an increase in power spectral entropy.

Table 1 lists the power spectral entropy values of the spectrogram before and after applying the proposed method. As the table shows, after two-dimensional homomorphic filtering, the power spectral entropy of the spectrogram decreases, indicating that the proposed method effectively restores the interference fringes of a high-speed vertically moving target in simulation experiments.

Table 1. The power spectral entropy of the spectrogram under high-speed condition.

	Origin IF	IF _{SD}	IF _{BD}
Spectral Entropy	29.96	14.07	10.62

Real high-speed targets often radiate signals containing not only broadband noise but also line-spectrum components. These line components typically have relatively high energy, which can overshadow the broadband interference fringes. Below, we analyze how to enhance interference fringes in such scenarios.

The simulation setup is the same as before, except that the target's radiated signal now includes line-spectrum components at [1050, 1310, 1420, 1600] Hz. Figure 13 shows the spectrogram in the presence of line-spectral interference. After normalization, the broadband spectrum's energy is relatively reduced.

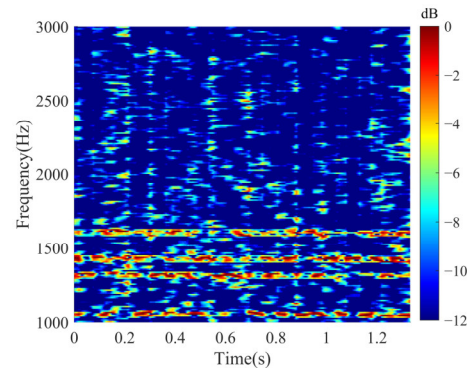


Figure 13. Spectrogram with line spectrum.

We again estimate the Doppler coefficients for the multipath signals, this time focusing on the 1800–3000 Hz band, and subsequently apply Doppler compensation based on these estimates. Figure 14 illustrates the (k_t, k_f) domain after taking the logarithm of the compensated spectrogram and performing a two-dimensional Fourier transform. The distribution in this domain closely resembles the case without line-spectrum signals. The main difference is that, when line-spectrum components are present in the target signal, a bright straight line appears at $k_t = 0$ in the (k_t, k_f) domain, corresponding to the line-spectrum signals in the time–frequency domain. Therefore, when designing the two-dimensional low-pass filter, one must exclude the region near $k_t = 0$ in the (k_t, k_f) domain to remove the line-spectrum components from the spectrogram. The passband used for the filter is shown in Figure 14.

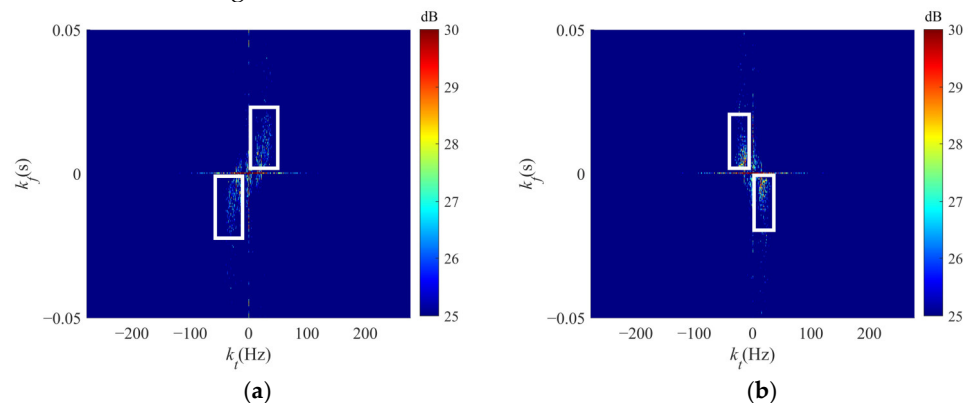


Figure 14. The (k_t, k_f) domain of the spectrogram containing line-spectrum after Doppler compensation. Here, white boxes represent two-dimensional low-pass filters: (a) The (k_t, k_f) domain corresponding to IF_{BD}; (b) The (k_t, k_f) domain corresponding to IF_{SD}.

Figure 15 shows the interference fringes after homomorphic filtering. Compared to Figure 12, it is evident that the interference fringes of the high-speed vertically moving target are effectively restored and enhanced, confirming the effectiveness of the proposed method in the presence of line-spectrum interference.

The IF_{BD} and IF_{SD} were calculated using Bellhop, respectively. According to Equation (5), the location of the interference fringes depends solely on the time delay differences among the multipath signals. Because seabed sediment parameters are typically unknown, the amplitude of the bottom-reflected signal cannot be accurately determined, and, thus, the database is constructed exclusively based on these multipath time-delay differences. These results were then subjected to matched filtering with the spectrogram in Figure 15 separately. Finally, the localization of the target was obtained, as shown in Figure 16. It can be seen from this figure that the proposed method can effectively locate a high-speed vertically moving target with a velocity of 90 knots. Specifically, depth estimation error is less than 4.4%, and range

error is below 2%. These results demonstrate that, under conditions of significant Doppler effects, strong line-spectrum interference, and low bottom-reflection coefficients, the proposed method can successfully separate and enhance IF_{BD} and IF_{SD} , thereby effectively estimating the position of high-speed vertically moving targets. The simulation results validate the algorithm's effectiveness.

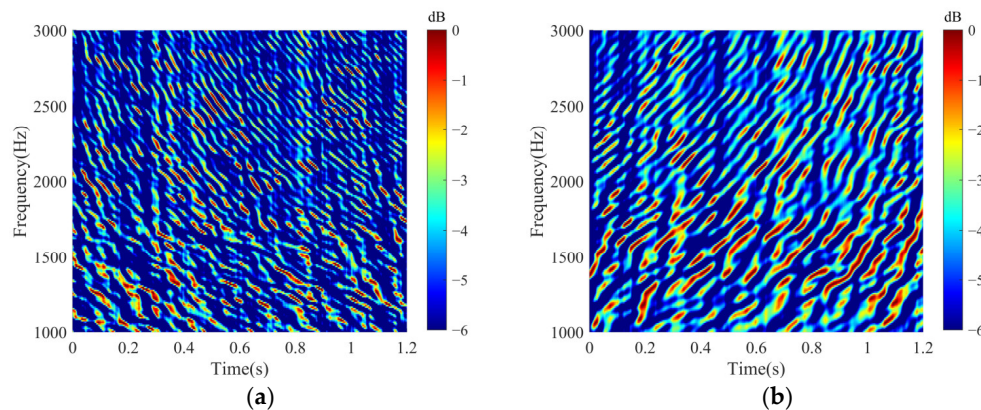


Figure 15. The spectrogram containing line-spectrum after two-dimensional homomorphic filtering: (a) IF_{BD} ; (b) IF_{SD} .

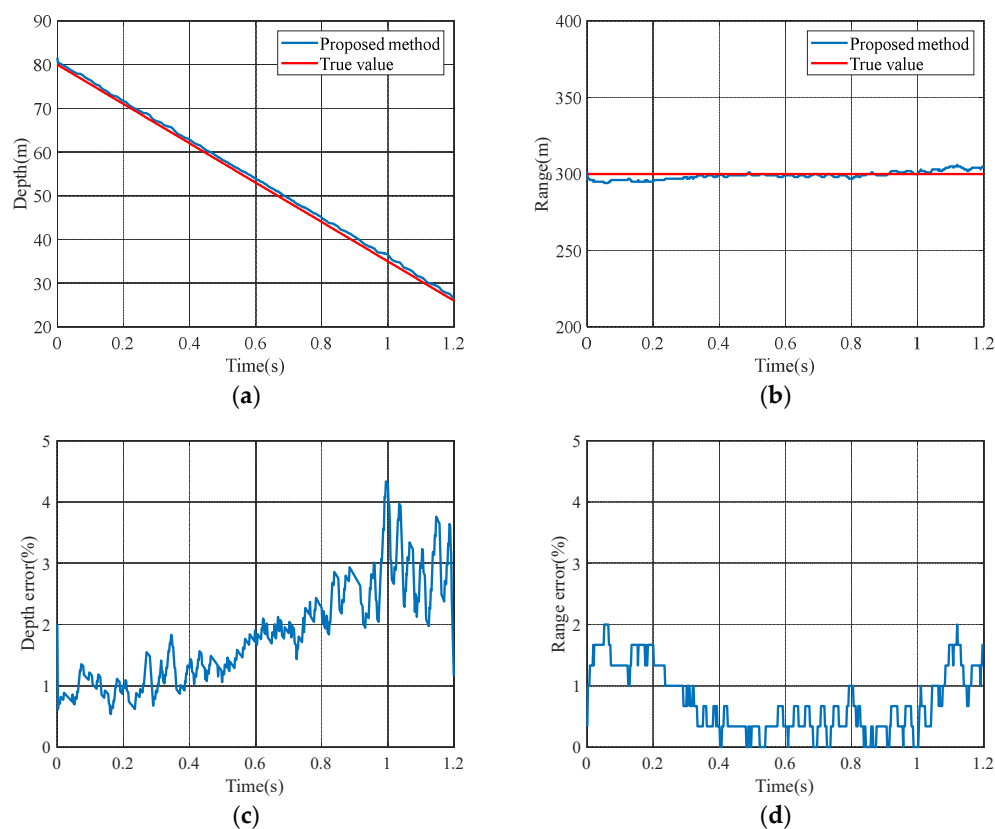


Figure 16. Target localization results of high-speed vertically moving target: (a) Depth estimation. (b) Depth error. (c) Range estimation. (d) Range error.

5. Lake Trial

To verify the proposed algorithm, we conducted a lake trial in April 2022 at Qian-dao Lake. In this experiment, we used an electric hoist to raise a sound source, thereby simulating the vertical motion of an underwater target. The water depth at the test site was approximately 67 m. Figure 17 shows the measured SSP and a schematic diagram of the experimental setup. During the trial, the ship's engine was turned off to minimize

interference from ship noise. A buoy-mounted hydrophone was employed to receive acoustic signals. The sound source emitted Gaussian white noise in the 1500~5000 Hz band. It was suspended at the stern of the ship and steadily hoisted from a depth of 40 m to 16 m over a period of 140 s. The hydrophone was located at a range of 136 m and at a depth of 41 m. STFT was performed on the received signals using a 1 s Hamming window with a 0.1 s sliding interval.

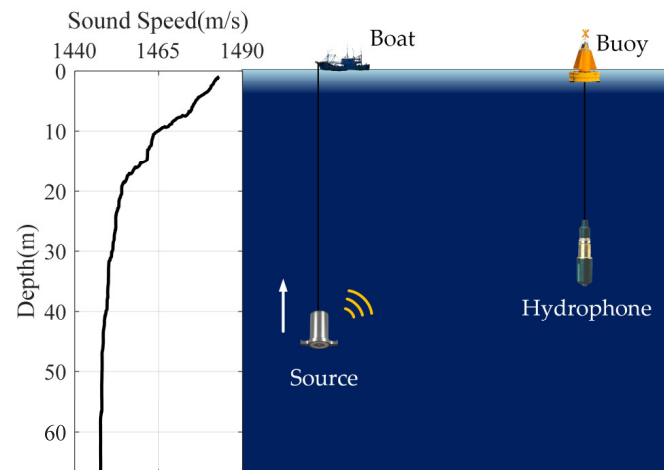


Figure 17. Experimental situation.

Figure 18 shows the spectrogram of the received signal, revealing that the interference structure is primarily composed of IF_{BD} and IF_{SD} . These two types of interference fringes overlap, and IF_{BD} , having a relatively low amplitude, becomes less distinct upon superposition with IF_{SD} . Moreover, owing to multiplicative noise, the fringe peaks (centerlines) in both IF_{BD} and IF_{SD} vanish.

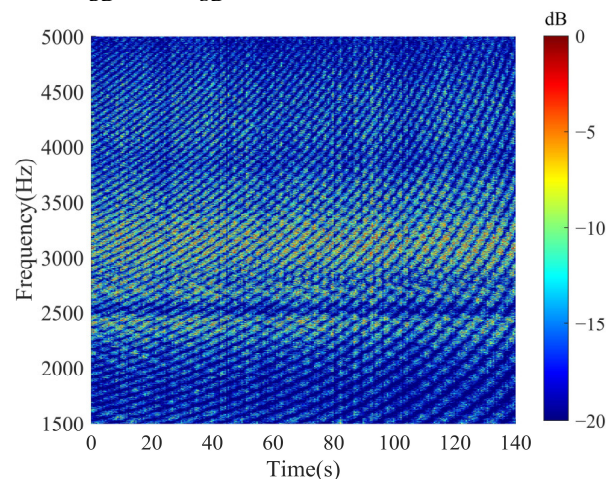


Figure 18. The spectrogram of the received signal.

Taking the logarithm of the spectrogram yields a logarithmic spectrogram, which is then transformed via a two-dimensional Fourier transform. Figure 19 shows the resulting (k_t, k_f) -domain distribution. Because the amplitude of the bottom-reflected signal is weaker than that of the surface-reflected signal, IF_{BD} exhibits lower amplitude. As a result, the low-frequency energy in quadrants I and III of the (k_t, k_f) -domain is much lower than that in quadrants II and IV. We then apply a two-dimensional low-pass filter to the low-frequency regions of quadrants I and III, as well as quadrants II and IV. The filter passband is depicted by the white boxes in Figure 19.

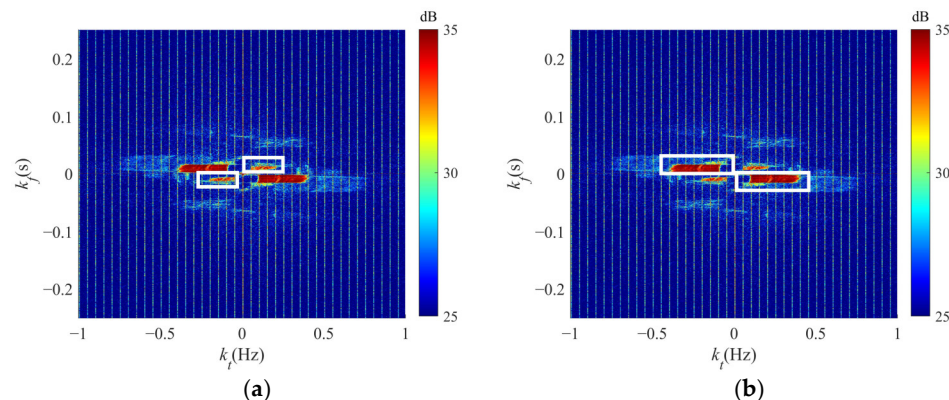


Figure 19. The two-dimensional low-pass filter within the (k_t, k_f) domain of the spectrogram. Here, white boxes represent two-dimensional low-pass filters: (a) The (k_t, k_f) domain corresponding to IF_{BD}; (b) The (k_t, k_f) domain corresponding to IF_{SD}.

Figure 20 displays the IF_{SD} and IF_{BD} interference fringes after homomorphic filtering. One can see that these two types of fringes have been effectively separated, and their fringe peaks (centerlines) are successfully restored.

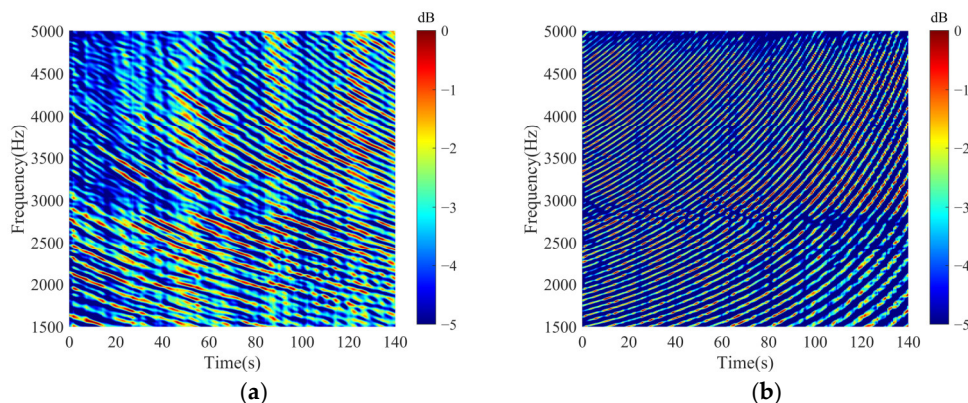


Figure 20. The spectrogram of the received signal after two-dimensional homomorphic filtering: (a) IF_{BD}; (b) IF_{SD}.

Table 2 shows the power spectral entropy of the spectrogram before and after homomorphic filtering. Before filtering, the spectrogram contains abundant multiplicative high-frequency components caused by the target's radiated noise, resulting in energy spread across the entire frequency band and thus higher power spectral entropy. After applying homomorphic filtering, not only does the stronger IF_{SD} become successfully separated from other components, but the previously overshadowed IF_{BD} peaks are also recovered. Because the high-frequency noise power spectrum is filtered out and the low-frequency periodic components of the interference fringes are restored, the power spectral entropy decreases. This result further demonstrates the effectiveness of the two-dimensional homomorphic filtering approach for interference fringe separation and enhancement.

Table 2. The power spectral entropy of the spectrogram in the lake trial.

	Origin IF	IF _{SD} After Filtering	IF _{BD} After Filtering
Spectral Entropy	174.25	12.12	11.52

The interference databases of the BD and SD were calculated separately using Bell-hop. Then, they were, respectively, processed through matched filtering with the data in Figure 20a,b. Finally, the localization results were obtained, as presented in Figure 21. As

can be seen from this figure, the proposed method can achieve the localization of the vertically moving target. The depth estimation errors are less than 1.8%, and range estimation errors are less than 2.2%. Analysis results indicate that the proposed method can effectively estimate the positions of vertically moving targets under strong negative layer underwater conditions. Moreover, the analysis of lake trail data further validates the effectiveness of the proposed method.

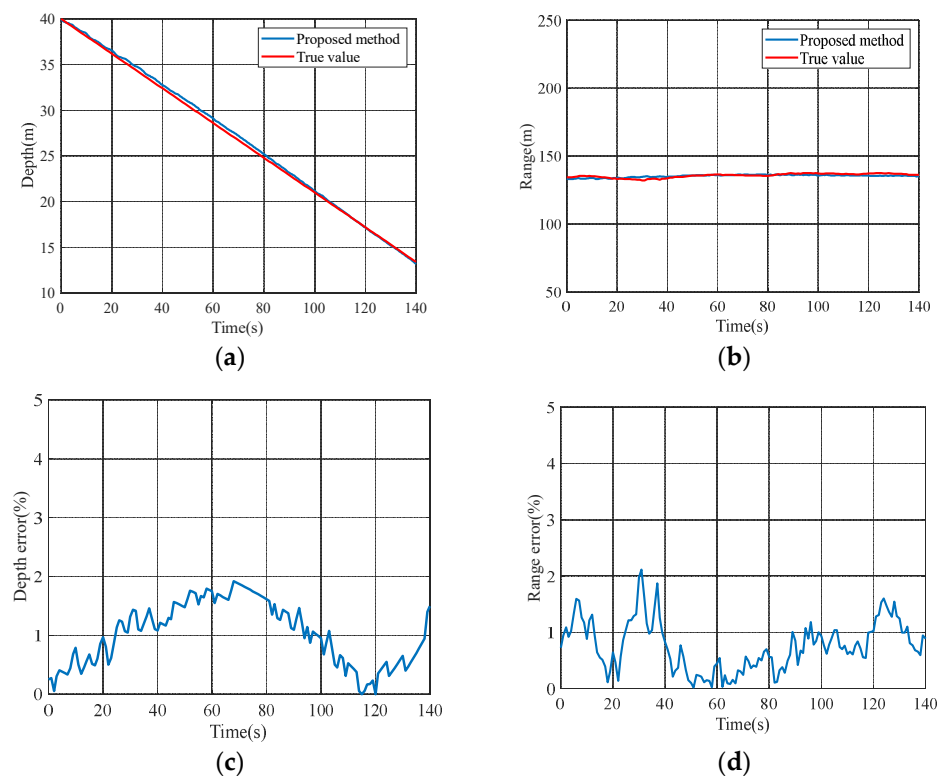


Figure 21. Target localization results in the lake trial: (a) Depth estimation. (b) Depth error. (c) Range estimation. (d) Range error.

6. Conclusions

This paper proposes a method for vertically moving target localization using a single hydrophone based on interference feature matching. Given that the interference fringes produced by vertically moving targets are easily affected by broadband radiated noise, line-spectrum interference, and significant Doppler effect among multipath signals, leading to reduced or lost fringe clarity, this study employs two-dimensional homomorphic filtering to separate and enhance these fringes. By exploiting the distribution characteristics of multipath interference fringes in the two-dimensional Fourier transform domain, the method applies a logarithmic transformation to convert multiplicative noise into additive noise. Subsequently, a low-pass filter is applied to effectively eliminate target noise and line-spectrum interference, thereby recovering the fringe peaks. Finally, localization is achieved by matching the interference with a preconstructed database. Simulation results demonstrate that the proposed method not only separates and enhances multipath interference fringes under conditions of strong line-spectrum interference and low bottom reflection but also effectively recovers fringes in high-speed vertically moving target sound fields, enabling successful localization. At a target speed of 90 knots, the depth errors are less than 4.4%, and the range errors are below 2%. The analysis of field data from Qiandao Lake shows that the depth estimation errors are below 1.8%, and range estimation errors are under 2.2%, which further verifies the algorithm's effectiveness, with experimental results consistent with theoretical prediction.

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Abbreviations

The following abbreviations are used in this manuscript:

STFT	Short-Time Fourier Transform
IF	Interference structure
SNR	Signal-to-noise ratio
SRBR	Surface-reflected–bottom-reflected

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