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Comparison of underwater acoustic propagation models for communication predictions

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Abstract. This study compares three acoustic propagation models, Bellhop, Kraken, and Scooter, within the Waymark-based underwater acoustic communication (UAC) framework. Sea-trial data collected in the northwest Pacific Ocean at distances of 42 km and 80 km are used for validation. The results show that all three models can reproduce the main multipath structures of the measured channels. Bellhop provides a computationally efficient and relatively sparse channel representation, but may miss part of the weak late-arrival components. In contrast, Kraken and Scooter preserve richer delayed multipath structures but require higher computational cost. These results indicate that both modeling accuracy and computational complexity should be considered when selecting propagation models for UAC channel prediction.

1. Introduction

Underwater acoustic communication (UAC) systems usually operate in highly dynamic channels characterized by time-varying multipath propagation [1, 2]. Hence, precise channel modeling is essential for the effective design, testing, and evaluation of these systems [3]. Despite significant progress in simulating underwater acoustic channels, particularly under static or quasi-static conditions, efficiently modeling the multipath channel remains challenging [4].

Specifically, communication systems tailored for a specific underwater channel often experience degraded performance when applied in varied environments. This calls for the use of resilient and generalizable models to precisely simulate the multipath channel, such as in ocean engineering scenarios [5]. Traditional underwater acoustic propagation models are generally established based on static or quasi-static assumptions, which can lead to considerable inaccuracies in dynamic ocean settings [6]. In reality, the time-varying nature of the ocean significantly impacts acoustic propagation paths and signal features [7]. Reflections from the sea surface and seabed, along with fluctuations in the sound-speed profile (SSP), cause multipath propagation that spreads signals over time and triggers inter-symbol interference (ISI) [8]. As a result, multipath propagation continues to be one of the most critical challenges for dependable underwater acoustic communications [9].

In this research, a systematic comparative analysis of three acoustic propagation models, Bellhop, Kraken, and Scooter, was conducted within the Waymark-based UAC framework to evaluate their effects on multipath prediction and computational complexity. The comparison



was validated using sea-trial data collected in the northwest Pacific Ocean at ranges of 42 km and 80 km. The results show that Bellhop provides a computationally efficient and relatively sparse channel representation, but may miss part of the weak delayed multipath structure under some long-range conditions. Kraken and Scooter, as wave-based models, can preserve richer delayed weak components and therefore provide a more complete description of the multipath structure, although their computational costs are much higher. This comparison clarifies the trade-off between multipath completeness and computational efficiency in long-range UAC channel prediction.

2. UAC channel modeling framework

Fig. 1 illustrates the overall framework for modeling a time-varying underwater acoustic channel. In this framework, the transmitter and receiver trajectories are discretized into spatial sampling points. At each waymark, an underwater acoustic propagation model is used to compute the channel response under the corresponding environmental and geometric conditions. The discrete channel snapshots are then processed by temporal interpolation to obtain a continuous representation of the channel evolution, and the resulting time-varying channel response is used to synthesize the received acoustic waveform.

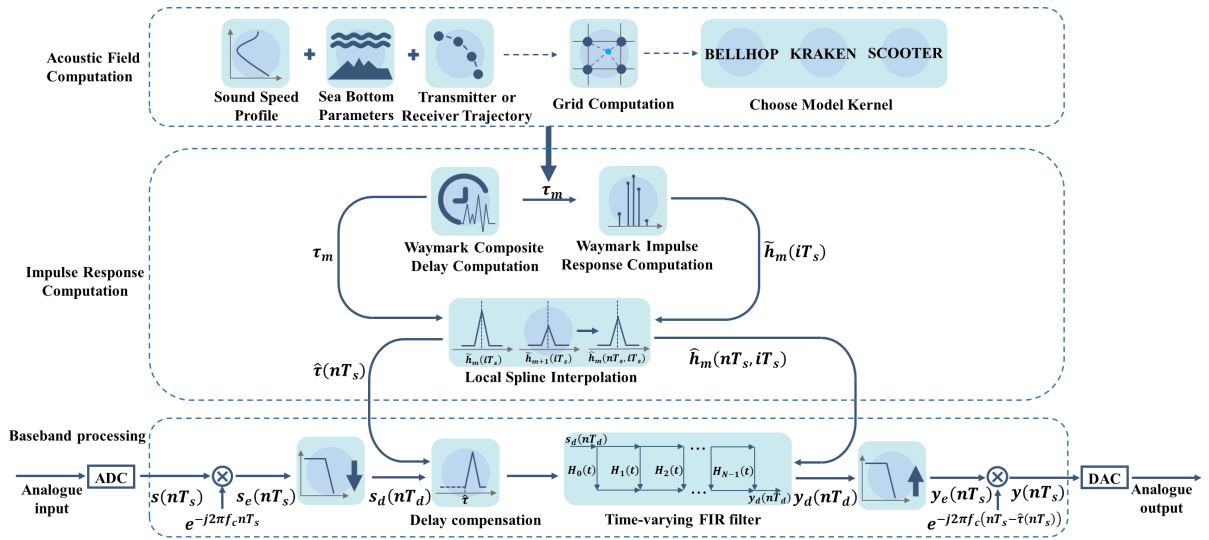


Figure 1. Block diagram of the UAC channel modeling framework.

2.1. Acoustic field computation

Following the Waymark principle, the relative transmitter/receiver (Tx/Rx) trajectory is sampled at sparse waymarks with a waymark interval T_w , which is much longer than the signal sampling interval T_s . For a transmitter moving with horizontal speed v_0 , the waymark interval should be chosen such that

$$T_w \ll \frac{T_s r}{\tau v_0}, \quad (1)$$

where r is the Tx/Rx horizontal distance and τ denotes the multipath delay spread. This condition ensures that the channel evolution between adjacent waymarks remains sufficiently smooth for subsequent interpolation.

At each waymark m , the channel frequency response $p(mT_w, \omega_k)$ is obtained from the selected underwater acoustic propagation model. In general, $p(mT_w, \omega_k)$ depends on the environmental

parameters, including the water density ρ , the sound-speed profile $c(z)$, the source depth z_s , the receiver depth z , and the horizontal Tx/Rx distance r . In this paper, the propagation model is chosen from Bellhop, Kraken, and Scooter.

2.2. Impulse response computation

Using the channel frequency response $p(mT_w, \omega_k)$, the waymark impulse response is reconstructed in the delay domain. To reduce the required delay support and improve interpolation consistency between adjacent waymarks, a waymark composite delay τ_m is introduced. Here, τ_m denotes the accumulated delay alignment applied to the m th waymark response so that adjacent waymark impulse responses are aligned before spline interpolation. The delay-adjusted waymark impulse response is written as

$$\tilde{h}_m(iT_s) = \Re \left\{ \frac{2}{K} \sum_{k=0}^{K-1} p(mT_w, \omega_k) e^{j\omega_k(iT_s + \tau_m)} \right\}, \quad (2)$$

where K is the number of sampled frequencies, ω_k is the k th angular-frequency sample, and i is the tap index.

After the waymark impulse responses have been obtained at discrete waymarks, the time-varying channel impulse response (CIR) is recovered by local spline interpolation. Specifically, adjacent waymark impulse responses $\tilde{h}_m(iT_s)$ are used to reconstruct the time-varying CIR at arbitrary signal sampling instants, denoted by $\hat{h}_m(nT_s, iT_s)$. The composite delay sequence is also interpolated in time and is later used for delay compensation in the signal-generation stage.

2.3. Baseband processing

The interpolated composite delay is written as

$$\hat{\tau}(nT_s) = \theta^T b(nT_s), \quad (3)$$

where θ is the vector of local spline coefficients associated with the composite-delay sequence, and $b(nT_s)$ denotes the corresponding spline basis vector.

Using the interpolated CIR, the baseband channel output is obtained through time-varying FIR filtering:

$$y_d(nT_d) = \tilde{s}_d^T(nT_d) \hat{h}_m(nT_d), \quad (4)$$

where T_d is the baseband sampling interval, $\tilde{s}_d(nT_d)$ is the delay-compensated input vector, and $\hat{h}_m(nT_d)$ is the interpolated time-varying CIR vector. The baseband output is then converted back to the passband signal. Through these steps, the framework generates the received signal using acoustic-field information at sparse waymarks, local spline interpolation of the time-varying CIR, and baseband-equivalent signal processing.

3. Incorporation of acoustic propagation models

3.1. Bellhop model: the ray-tracing method

Incorporation process. Fig. 2 illustrates the integration of Bellhop [10] within the UAC channel modeling framework.

After obtaining the environment file, Bellhop computes the arrivals at each waymark. The arrival amplitudes and delays are treated as approximately frequency-independent and are denoted by a_{ml} and τ_{ml} .

The channel frequency response is written as

$$p(mT_w, \omega_k) = \sum_{l=1}^{L_m} a_{ml} e^{-j\omega_k \tau_{ml}}, \quad (5)$$

where L_m is the number of arrivals at the m th waymark.

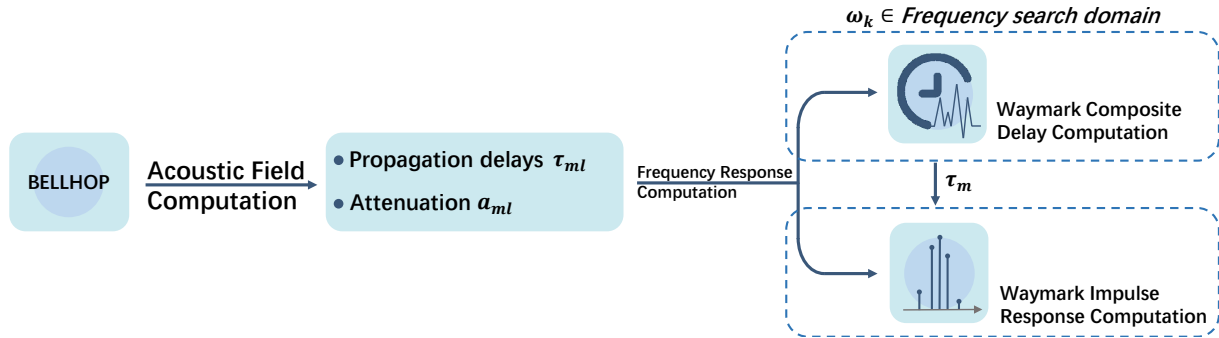


Figure 2. Workflow of Bellhop model incorporation.

3.2. Kraken model: the normal-mode method

Incorporation process. Fig. 3 illustrates the complete integration process of the Kraken model [11].

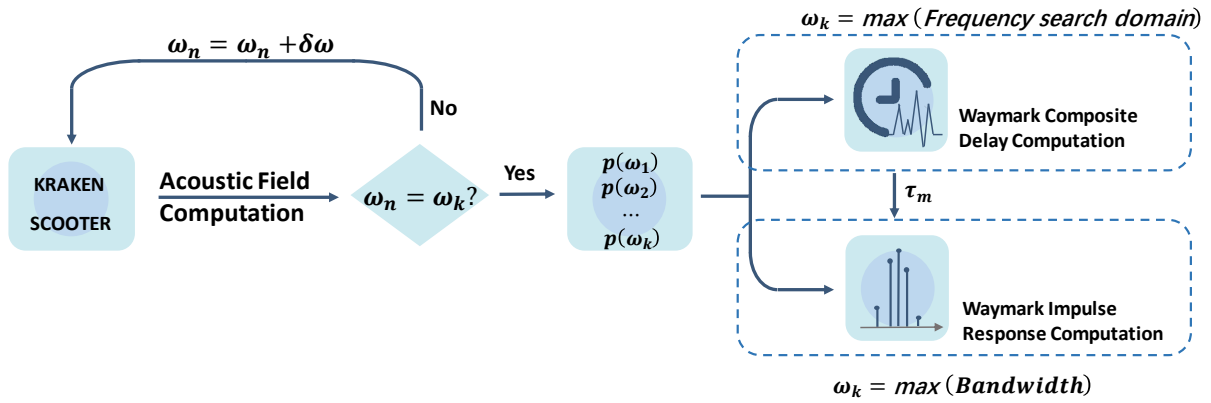


Figure 3. Incorporation process of the Kraken/Scooter model.

The Kraken model computes the frequency response at ω_k under the assumption of a range-independent environment [11]:

$$p(mT_w, \omega_k) = \sum_{q=1}^{Q(\omega_k)} R_q(\omega_k, r(mT_w)) Z_q(\omega_k, z(mT_w)), \quad (6)$$

where $Z_q(\omega_k, z)$ stands for the normal modes, and $R_q(\omega_k, r)$ signifies the associated expansion coefficients. By utilizing the frequency response $p(mT_w, \omega_k)$ obtained from the Kraken model, the time-domain CIR for every waymark is determined via Fourier inversion, thereby allowing its incorporation into subsequent calculations.

3.3. Scooter model: the wavenumber-integration method

Incorporation process. Fig. 3 depicts the workflow for the integration of the Scooter model. Regarding the wavenumber integration method, the frequency response at ω_k is computed under

the assumption of a range-independent configuration [12]:

$$p(mT_w, \omega_k) = \int_0^\infty \phi(k_r, z(mT_w)) J_0(k_r r(mT_w)) k_r dk_r, \quad (7)$$

where $J_0(k_r r(mT_w))$ stands for the Bessel function, and $\phi(k_r, z(mT_w))$ indicates the wavenumber function, which fulfills the depth equation:

$$\frac{\partial^2 \phi}{\partial z^2} + (k^2 - k_r^2) \phi = -2\delta(z - z_s), \quad (8)$$

where k denotes the wave number of the medium, and δ represents the Dirac delta function. The frequency response $p(mT_w, \omega_k)$ is directly utilized to reconstruct the CIR for every waymark, enabling precise modeling of time-varying acoustic channels.

4. Sea-trial results

Fig. 4 illustrates the sea-trial configuration, where the water depth was roughly 5 km and the sound speed profile (SSP) had its minimum value at a depth of 300 m. The transmitter was towed at a depth of 200 m with a speed of 6 m/s, whereas the receiver was deployed at a depth of 400 m and treated as stationary during the selected analysis interval. In each trial, an orthogonal frequency-division multiplexing (OFDM) signal with a carrier frequency of 3072 Hz [13] was transmitted, lasting for 14 s. Fig. 5 displays the ray-tracing propagation structure obtained using the Bellhop model, which shows considerable acoustic attenuation during long-range propagation.

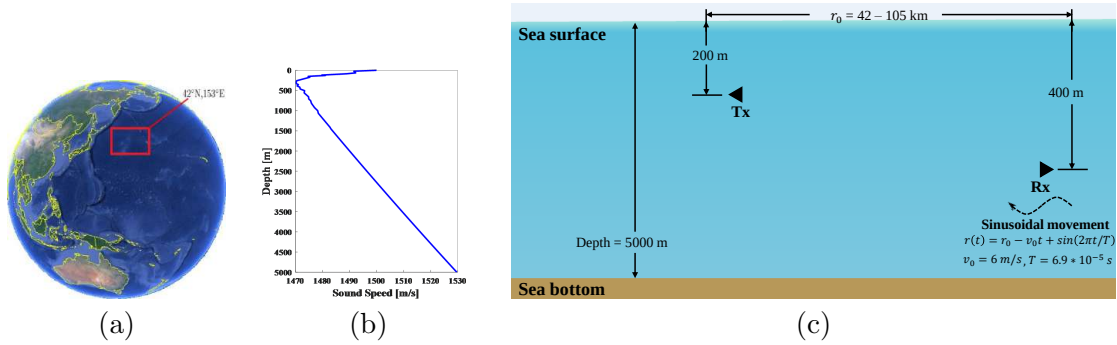


Figure 4. (a) Sea-trial area in the northwest Pacific Ocean; (b) SSP; and (c) scenarios of the sea trial featuring Tx/Rx distances of 42 km and 80 km and a water depth of 5 km [13].

4.1. Sea trial at 42 km

Multipath precision. Fig. 6 illustrates the variations in the channel impulse response derived from the sea trial and the UAC simulation using three propagation models at a 42 km distance. The Bellhop-based UAC simulation can reproduce the initial two arrivals and several later arrivals within the time span of 80 ms to 115 ms. These arrivals can be considered as components of the actual sparse arrivals found in the sea-trial data. In contrast, the UAC simulations employing the Kraken and Scooter models are capable of predicting not only the first two arrivals but also more subsequent arrivals beginning at 80 ms and ending at 160 ms. These subsequent arrivals also show a sparse distribution. There is no marked distinction between the UAC simulation outcomes based on the Kraken and Scooter models.

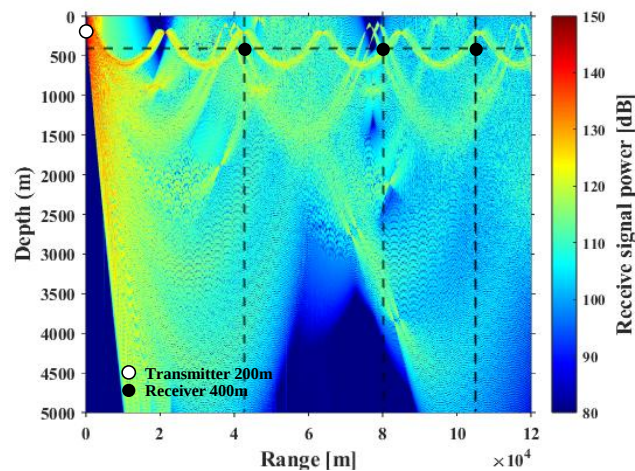


Figure 5. The principal propagation paths of acoustic rays and simulated received signal power. The transmitter was towed at a depth of 200 m, while the receiver was towed at a depth of 400 m.

To examine the similarity between the sea-trial data and the three simulation results, a cross-correlation analysis was carried out. Fig. 7(a) displays the cross-correlation outcomes, which reveal positive correlations. The average correlation value is 0.60 for the Bellhop-based simulation, 0.65 for the Kraken-based simulation, and 0.67 for the Scooter-based simulation (table 1). The results show that the accuracy of the Bellhop-based simulation is roughly 8% lower than that of the Kraken-based simulation and 12% lower than that of the Scooter-based simulation. The Scooter-based simulation is slightly more accurate than the Kraken-based simulation.

Table 1. Correlation results.

Distance [km]	Bellhop	Kraken	Scooter
42	0.60	0.65	0.67
80	0.68	0.81	0.84

4.2. Sea trial at 80 km

Multipath precision. Fig. 8 shows the changes in the channel impulse response from the sea trial and UAC simulations using three propagation models at 80 km. The Bellhop-based UAC channel simulation can predict the main arrivals with delays below 125 ms, while the delayed arrival around 150 ms is not clearly reproduced. However, the Kraken- and Scooter-based UAC simulations can predict not only the main arrivals with delays under 125 ms but also the main arrival at around 150 ms, providing more detailed path information between these main arrivals.

Fig. 7(b) displays cross-correlation results, which show positive correlations. The average cross-correlation values are 0.68 for the Bellhop-based simulation, 0.81 for the Kraken-based simulation, and 0.84 for the Scooter-based simulation (table 1). These results indicate that

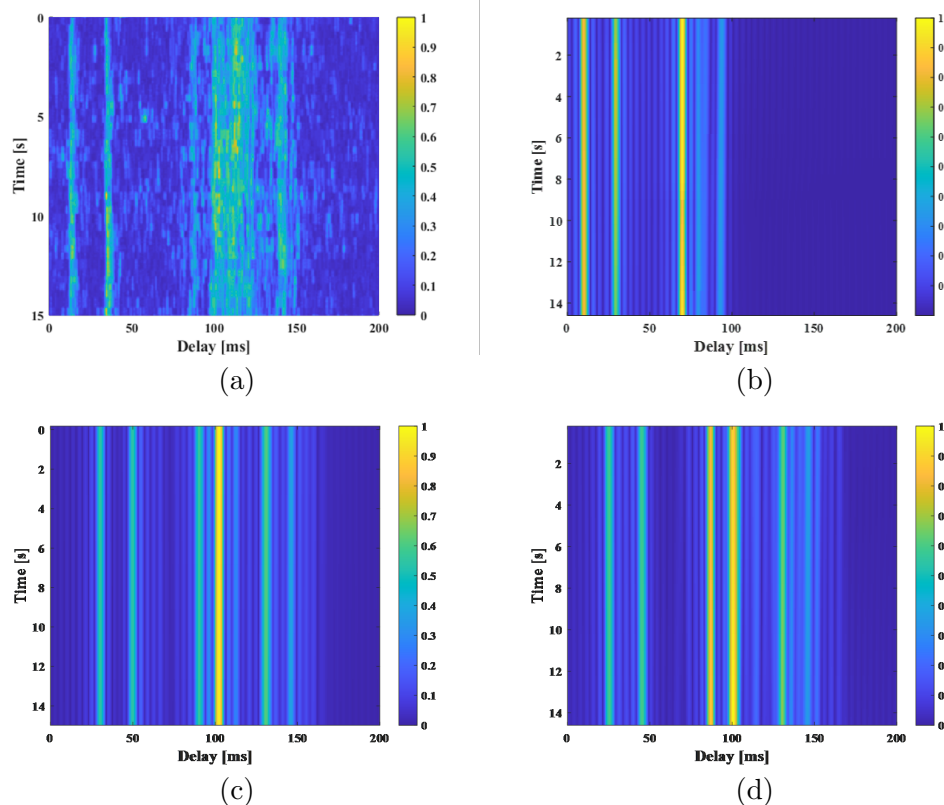


Figure 6. Fluctuations of the channel impulse response, which signify multipath, at a transmitter/receiver (Tx/Rx) distance of 42 km: (a) sea-trial data [13], (b) UAC modeling based on the Bellhop model, (c) UAC modeling based on the Kraken model, and (d) UAC modeling based on the Scooter model.

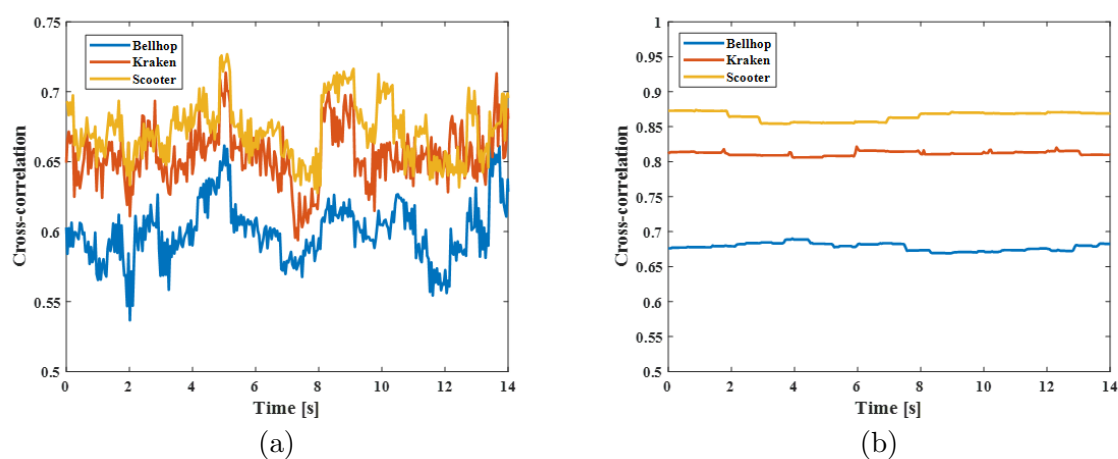


Figure 7. Cross-correlation results between the sea-trial multipath and the modeled UAC multipath using the three models at distances of (a) 42 km and (b) 80 km.

the accuracy of the Bellhop-based simulation is about 19% lower than that of the Kraken-based simulation and 24% lower than that of the Scooter-based simulation. The Scooter-based simulation has slightly higher accuracy than the Kraken-based simulation.

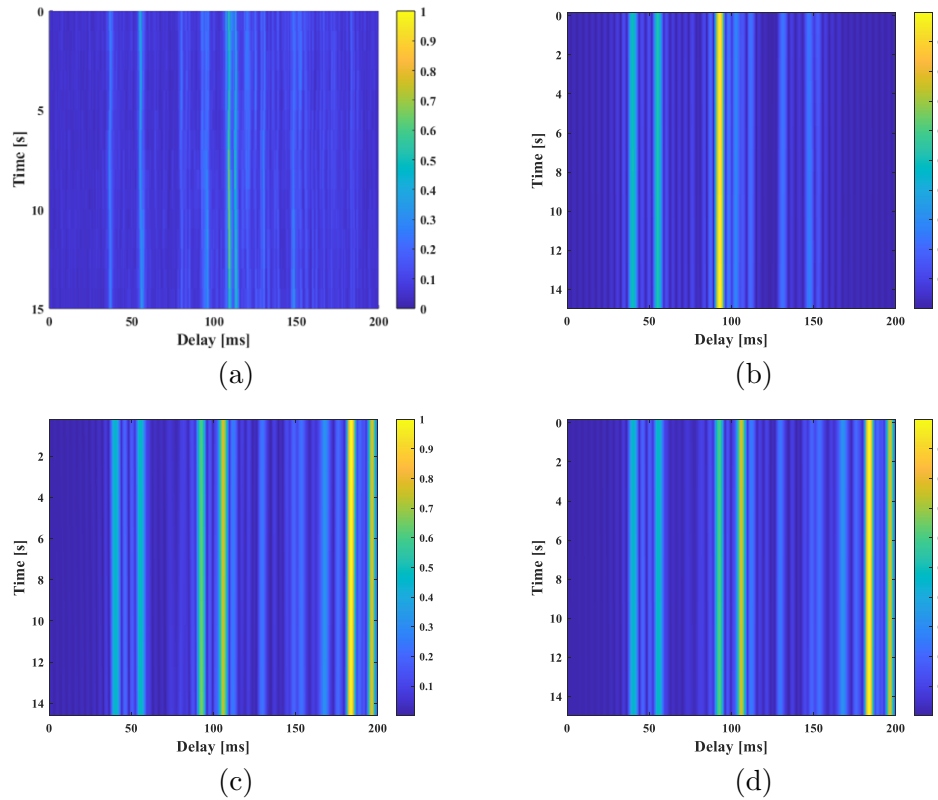


Figure 8. Fluctuations of the channel impulse response, indicating multipath, at a transmitter/receiver (Tx/Rx) distance of 80 km: (a) sea-trial data [13], (b) UAC modeling based on the Bellhop model, (c) UAC modeling based on the Kraken model, and (d) UAC modeling based on the Scooter model.

Complexity comparison. Table 2 presents the computational complexity for UAC simulations using the three models. Clearly, the simulation utilizing the Bellhop model requires significantly lower computational cost than the other two simulations.

Table 2. Computational complexity comparison.

Range [km]	Bellhop	Kraken	Scooter
42	4.20×10^6	1.51×10^8	1.65×10^9
80	8.00×10^6	2.87×10^8	5.81×10^9

5. Conclusions and discussion

This study evaluated the trade-off between multipath accuracy and computational complexity for three underwater acoustic propagation models, Bellhop, Kraken, and Scooter, in UAC

predictions. To confirm the effectiveness of these models within a UAC channel modeling framework, sea-trial data from the northwest Pacific Ocean at distances of 42–80 km and a sea depth of 5 km were used. The results show that the simulation data from the three models match reasonably well with the sea-trial data. Moreover, simulations based on Kraken and Scooter show higher multipath accuracy than those based on Bellhop, especially in preserving weak delayed multipath components. In contrast, Bellhop-based simulations are more computationally efficient but may provide a sparser description of the multipath structure. These findings highlight the importance of balancing accuracy and complexity when choosing models for real-world underwater acoustic communication simulations, such as the prediction of multipath structures.

Acknowledgments

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