Ray-Path Modeling in Layered Water Columns and Its Impact on Echo-Sounding Depth Accuracy

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ABSTRACT

The paper investigates the impact of the acoustic ray path in a stratified seawater environment on the accuracy of echo sounding measurements for marine mapping. Based on the theory of acoustic refraction (continuous form of Snell's Law) and the Sound Speed Profile (SSP) model, the study develops a ray-tracing–based computation and correction procedure, validated using sound velocity data from the Khanh Hoa–Binh Thuan region. Two approaches for calculating the acoustic travel path are directly compared with the theoretical distance of 500 m: (i) the layer-averaged travel time approach yields 512.717 m (an error of ±12.717 m); and (ii) the mean velocity for the entire water column combined with the actual measured travel time yields 499.974 m (an error of ±0.026 m). Comparison with national standards shows that approach (i) exceeds the allowable limits of TCVN 10336:2015 – Class 3 (±11.543 m at 500 m) and TCVN 10337:2015 – Class B (±11.0 m), while approach (ii) meets and surpasses both standards. The results confirm that assuming a uniform sound velocity or applying layer-averaged timing without ray-tracing may lead to systematic errors of several meters at a 500 m depth. The paper recommends acquiring in-situ SSP data (via CTD/XBT) at sufficiently high temporal and spatial frequency, and integrating ray-tracing methods throughout the multibeam echo-sounding processing chain to ensure compliance with TCVN standards when producing marine maps for national defense, socioeconomic development, and climate change adaptation purposes.

KEYWORDS: *acoustic ray path, sound speed profile-SSP; acoustic refraction; echo sounding; ray-tracing*

1 INTRODUCTION

In the context of climate change, where ocean warming, sea-level rise, and rapidly changing hydrographic structures are occurring, the demand for accurate depth surveying has become increasingly urgent to support maritime safety, marine spatial planning, and the protection of coastal infrastructure [1]. In parallel, the 'Decade of Ocean Science for Sustainable Development 2021–2030,' initiated by the United Nations, calls for strengthening ocean data and knowledge to inform science-based decision-making [2]. From a technical and legal perspective, 'SOLAS Chapter V' requires vessels to be equipped with adequate and

timely updated nautical charts [3], while IHO S-44 specifies the standards for hydrographic surveys to ensure the quality of data for maritime safety [4]. In seafloor bathymetry, echo-sounding technology (single-beam and multibeam sonar) is widely used due to its capability to acquire wide-area data with high resolution [5, 6]. However, in a seawater environment stratified by temperature and salinity, the refraction (bending) of acoustic rays causes the actual transmission path (ray path) to be curved, differing completely from the straight-line assumption of the conventional depth measurement principle. Neglecting the refraction effect can lead to significant systematic errors in depth determination, often ranging from several meters to tens of meters at greater depths, directly threatening compliance with the Total Vertical Uncertainty (TVU) requirements specified by IHO S-44. Therefore, correcting the acoustic ray path using ray-tracing models has become a mandatory standard method in modern multibeam hydrography [7-9].

The East Sea region, particularly the South Central coastal waters from Khanh Hoa to Binh Thuan, represents a complex testing environment due to the strong influence of monsoons, seasonal upwelling, and the presence of thermohaline fronts. These dynamic factors generate sound velocity gradients both vertically and horizontally, causing the SSP to vary continuously and exhibit anisotropic characteristics. In the East Sea, previous hydrographic surveys have characterized the general seasonal variation of sound speed, notably the strong surface thermocline during the southwest monsoon [10-12]. However, most of these studies remain descriptive, with limited analysis of quantitative effects on acoustic ray paths or multibeam depth accuracy [13]. Furthermore, the lack of large-scale, long-term oceanographic data has restricted regional modeling of SSP variability and its implications for bathymetric correction. To bridge this gap, this study employs a comprehensive dataset of sound-speed measurements from the Khanh Hoa–Binh Thuan waters to evaluate how stratification alters acoustic ray trajectories and depth accuracy. The analysis integrates ray-tracing simulation and empirical travel-time methods to assess the degree of deviation under different SSP conditions.

This paper aims to quantify depth measurement errors in the Khanh Hoa–Binh Thuan region by applying a 2D ray-tracing model based on statistically derived SSP from in-situ measurements. The main contribution of this study is the numerical demonstration that not using ray-tracing leads to errors exceeding the TCVN threshold at a depth of 500 m. Accordingly, the paper provides specific technical recommendations on SSP acquisition and the integration of ray-tracing into the data processing workflow to ensure data quality for maritime safety and marine economic development objectives.

The research objectives of this paper include:

(i) Establishing a theoretical basis and developing a procedure for calculating the acoustic ray path in a stratified seawater environment;

(ii) Applying sound velocity data from the Khanh Hoa–Binh Thuan region to simulate the acoustic ray path and compare various depth calculation methods;

(iii) Assessing depth accuracy against current national standards and providing recommendations for the application of echo-sounding technology in marine mapping to support national defense, socio-economic development, and climate change research.

2 STUDY AREA AND DATA

2.1 Study area

The study area is located along the coast of Central Vietnam, extending from Khanh Hoa to Binh Thuan provinces, defined by the coordinates: Latitude 09°40′00″N to

12°46′00″N and Longitude 108°00′00″E to 112°30′00″E. This sea area holds a strategic role for national defense and security while being crucial for socio-economic development. The region belongs to the tropical monsoon climate zone, characterized by high average temperatures (approximately 26°C) and sea salinity ranging from 30-33‰.

The hydrographic characteristics here are quite complex, notably influenced by the seasonal variation of hydrodynamic factors: (1) Seasonal reversal of coastal currents (northeast-southwest during winter and vice versa during summer); (2) The formation of summer upwelling; (3) Strong impacts from the Northeast and Southwest monsoons, which cause changes in wave intensity and nearshore tidal regimes. These factors lead to significant variations in the Sound Speed Profile across the region, changing intensely with depth, temperature, and salinity. This makes the area a challenging and representative environment for quantitatively assessing the accuracy of echo-sounding technology

2.2 Data

To simulate the acoustic ray path and assess the influence of the Sound Speed Profile (SSP) in the study area, a detailed dataset of oceanographic observations concerning sound velocity variation with depth is required. Based on available East Sea oceanographic data, the research team collected and synthesized mean sound velocity values at standard water layers from the sea surface down to a depth of 500 m, while also recording the number of measurements at each depth. The dataset includes over 124,000 meteorological-hydrographic observation stations from the period 1817–2007, and updated data from 2007 to the present from more than 1,600 continuous, broad-area measurement stations. In this study, we utilize the sound velocity data at standard water layers to calculate and simulate the acoustic ray path. In addition to the mean values, the number of measurements (or the number of acoustic rays) helps assess the data reliability, shallower layers typically have more measurements, whereas deeper layers have fewer, leading to lower reliability. The detailed statistics are presented in Table 1.

Table 1. Average sound velocity and number of measurements by depth in the Khanh Hoa - Binh Thuan sea area

Tab 1. Średnia prędkość dźwięku oraz liczba pomiarów według głębokości w obszarze morskim Khánh Hòa – Bình Thuận.

No.	Depth (m)	Average sound velocity (m/s)	Sound transmission time (s)	Number of measurements
(1)	(2)	(3)	(4)	(5)
	0			733
1		1536.62	0.007	
	10			826
2		1537.20	0.007	
	20			–
3		1534.46	0.007	
	30			1081
4		1529.84	0.013	
	50			869
5		1524.71	0.016	
	75			517
6		1521.38	0.016	
	100			260
7		1518.03	0.016	

No.	Depth (m)	Average sound velocity (m/s)	Sound transmission time (s)	Number of measurements
	125			168
8		1514.51	0.017	
	150			148
9		1508.75	0.033	
	200			125
10		1504.42	0.033	
	250			98
11		1501.11	0.033	
	300			88
12		1495.33	0.067	
	400			29
13		1493.51	0.067	
	500			3
Average		1516.91	0.026	

The statistical results in Table 1 indicate that the sound velocity in the study area generally exhibits a decreasing trend with depth, which is particularly evident in the 0–300 m layer. The reduction in sound velocity in the surface water layer reflects the strong influence of temperature, which rapidly diminishes as one descends below the sea surface. Conversely, at deeper layers (≥ 400 m), the variation in sound velocity is less pronounced, mainly due to the increasing effect of pressure. The number of measurements also decreases significantly with depth: from hundreds to over a thousand in the shallow water layer, down to only a few dozen measurements at 400 m, and just 3 measurements at 500 m. This suggests that the data reliability in deeper layers is lower, simultaneously highlighting the difficulty of conducting oceanographic surveys in the deep seafloor area.

The trend of sound velocity decreasing with depth is the reason why acoustic rays emitted from the source are generally bent downwards, exactly as analyzed in Section 2. Therefore, the Sound Speed Profile (SSP) statistically derived from real-world data is crucially important for simulating the acoustic ray path using the layered model, in order to assess and correct errors during multibeam echo sounding in the Khanh Hoa - Binh Thuan sea area.

To visualize the variation in sound velocity with depth, the research team constructed the Sound Speed Profile (SSP) for the study area based on the statistical data in Table 1. This chart clearly illustrates the change in sound velocity within the water column, reflecting the combined effects of temperature, salinity, and pressure at varying depths. The SSP serves as a crucial foundation for ray-tracing models, as the shape of the sound velocity curve determines the direction of bending of the acoustic ray path and the magnitude of error in echo sounding. Figure 1 illustrates the average SSP for the Khanh Hoa – Binh Thuan area.

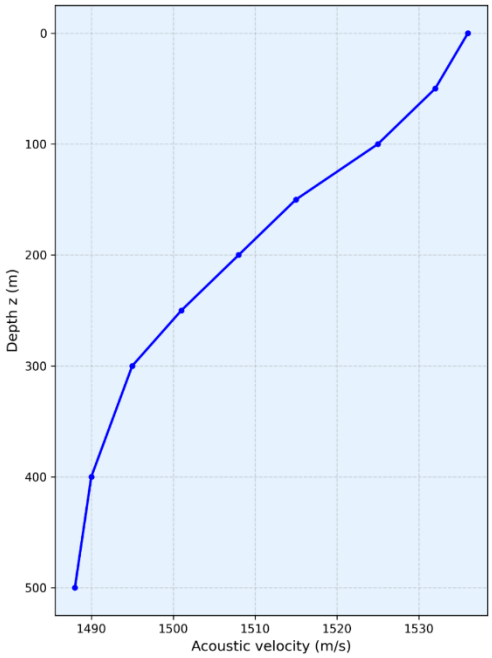

Figure 1. Sound Speed Profile (SSP) versus Depth in the Khanh Hoa–Binh Thuan Area

Rys 1. Profil prędkości dźwięku (SSP) w funkcji głębokości w rejonie Khánh Hòa – Bình Thuận.

Figure 1 shows that the sound velocity in the study area reaches its highest value in the surface water layer (approximately 1537 m/s) and gradually decreases with depth. In the 0–100 m layer, this reduction occurs quite rapidly, primarily due to the sharp decrease in temperature with depth. Between 100 and 300 m, the rate of decrease slows down but still maintains a steady downward trend, reflecting the combined influence of both temperature and salinity. In deeper layers (≥ 400 m), the sound velocity is nearly stable, exhibiting minimal variation and being predominantly governed by the increasing pressure with depth. This characteristic is significantly important for acoustic ray path simulation. The decrease in sound velocity in the surface layer causes the acoustic rays to be bent downwards, creating curved ray paths instead of the straight lines assumed in Formula (1). Therefore, the SSP not only helps explain the phenomenon of sound refraction in the Khanh Hoa – Binh Thuan sea area but is also the mandatory input parameter for correcting errors in echo sounding, contributing to improving the accuracy of determining the depth of the seabed terrain.

3 METHODOLOGY

The echo-sounding method determines water depth based on the travel time of an acoustic pulse from the transmitter to the receiver after reflection. Under the assumption of a homogeneous medium with a constant sound velocity, the depth H is calculated using Equation (1)

$$H = \frac{C.\Delta t}{2} \tag{1}$$

Where:
- H: Depth (m)
- C: Sound velocity in water (m/s)

- Δt: Time from signal transmission to reception (s).

Formula (1) is simple and widely used in single-beam and multibeam echo-sounding systems. However, it is only accurate when the sound velocity is considered constant. In reality, sound velocity varies with temperature, salinity, and pressure, etc., leading to significant errors if only an average value is used [7]

The seawater environment is non-homogeneous, therefore, sound velocity varies with numerous oceanographic factors, among which the most significant are temperature, salinity, and pressure, etc [14]. This variation prevents sound velocity from remaining constant, causing it to change with depth and thus creating the SSP.

When a sound velocity gradient exists in the vertical direction, the acoustic ray emitted from the source will not travel in a straight line but will be bent according to the law of refraction. Specifically:

- If the sound velocity increases with depth (for example, when passing from the cold surface water layer to warmer, compressed water at greater depths), the acoustic ray will be gradually bent and tend to turn back towards the water surface.

- If the sound velocity decreases with depth (for example, when passing from a warm surface water area to a colder water layer below), the acoustic ray will be bent downwards.

This phenomenon follows to Fermat's Principle and is described by Snell's Law for continuously variable media [7]:

$$R = \frac{C_0}{G.\cos\theta_0} \tag{2}$$

Where:

- θ(z): the angle between the acoustic ray and the horizontal at depth z,
- C(z): the sound speed at depth z.

Expression (2) is the generalized form of Snell's Law when the medium has a sound velocity gradient that changes continuously with depth, rather than discretely in layers. It demonstrates an inverse relationship between sound velocity and the angle of propagation: when the sound velocity decreases, the inclination angle increases and the acoustic ray curves downward; conversely, when the sound velocity increases, the inclination angle decreases and the acoustic ray curves upward. A direct consequence of this phenomenon is that the actual path length of the acoustic ray is longer than the straight-line assumption used in Formula (1), leading to errors in depth calculation if only the average velocity is used. In marine areas with significant changes in hydrographic structure (such as continental shelf edges or regions with thermal or salinity eddies), this error can reach tens of meters, significantly affecting the quality of nautical charts

Expression (2) is the general form of Snell's law when the environment has a continuously varying sound velocity gradient with depth, rather than discrete layers. It shows an inverse relationship between sound velocity and transmission angle: when sound velocity decreases, the inclination angle increases and the acoustic ray bends downward; conversely, when sound velocity increases, the inclination angle decreases and the acoustic ray bends upward. The direct consequence of this phenomenon is that the actual path of the acoustic ray is longer than the assumed straight line in formula (1), leading to errors in depth calculation if only the average velocity is used. In marine areas with strong variations in hydrological

structure (such as continental shelf edges or areas with thermal and salinity eddies), this error can reach tens of meters, significantly affecting the quality of nautical charts.

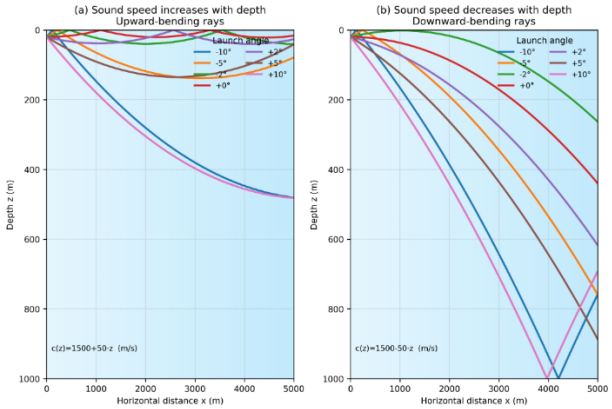

Figure 2. Acoustic ray path in a sound velocity gradient environment

Rys 2. Tor propagacji promienia akustycznego w środowisku o gradiencie prędkości dźwięku.

Figure 2 illustrates the acoustic ray paths in two simplified stratified environments: (a) When the sound speed increases with depth (c(z)=1500+50z), the acoustic rays bend upward toward the surface. (b) When the sound speed decreases with depth (c(z)=1500−50z), the rays bend downward toward deeper layers. The results illustrate the influence of positive and negative sound-speed gradients on ray curvature, in accordance with Snell's law for continuously stratified ocean environments. Each colored curve corresponds to a different launch angle relative to the horizontal direction at the source depth.

To accurately simulate the acoustic ray path in a realistic marine environment, a common approach is to divide the water column into thin layers, where the sound velocity gradient is assumed to be constant. This approach simplifies the analysis of the ray path within each layer while still reflecting the non-linear variation of the overall SSP [7].

In a homogeneous layer with a sound velocity gradient G, the sound ray path has the shape of a circular arc. The radius of curvature R and the center coordinates (x_0, z_0) are determined by:

$$R = \frac{C_0}{G.\cos\theta_0} \tag{3}$$

$$x_0 = x_s - R.\sin\theta_0\,,\ z_0 = z_s + R.\cos\theta_0 \tag{4}$$

Where:

- C_0: Sound velocity at the transmission point,
- θ_0: Angle of acoustic ray emission relative to the horizontal direction
- (x_s, z_s): Coordinates of the emission point
- G: The vertical gradient of sound velocity.

The equation of the circular path of the acoustic ray in the layer from the generator to depth z has the form:

$$(x - x_0)^2 + (z - z_0)^2 = R^2 \tag{5}$$

When the acoustic ray meets the interface between two layers, the new propagation direction is determined based on Snell's law:

$$\frac{\sin\theta_1}{C_1} = \frac{\sin\theta_2}{C_2} \tag{6}$$

Where: C_1, C_2 are the average sound velocity of two adjacent layers, θ_1, θ_2 are the angles of incidence and angle of refraction, respectively

The path calculation process is carried out sequentially:

- Initialize the acoustic ray at the source with the initial angle θ_0.
- Calculate the radius of curvature and the coordinates of the center using (3) and (4).
- Determine the intersection with the interface by solving (5)
- Calculate the new angle of refraction using (6)
- Repeat until the acoustic ray hits the seafloor or undergoes total reflection.

This layering method is widely applied in sound propagation modeling, such as Bellhop, KRAKEN and other ray-tracing tools, thanks to its balance between accuracy and computational efficiency [7].

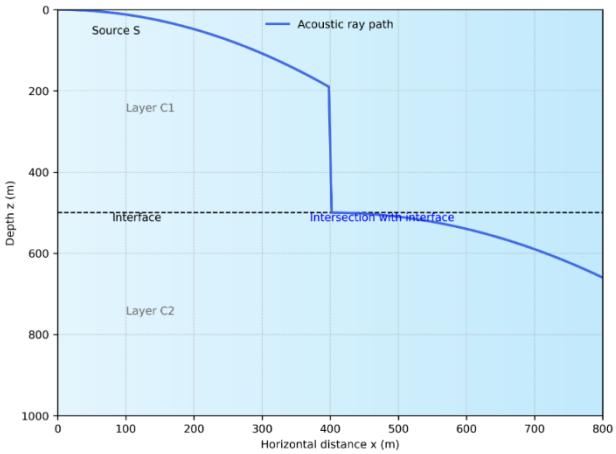

Figure 3. Acoustic ray path across two water layers and the intersection at the interface

Rys 3. Tor propagacji promienia akustycznego w dwóch warstwach wody oraz punkt przecięcia na granicy warstw.

Figure 3 illustrates an acoustic ray emitted from a source S in the upper water layer (C1). The interface separates two distinct layers characterized by different sound-speed gradients. Upon reaching this interface, the ray undergoes refraction, which is governed by Snell's Law, resulting in an abrupt change in the ray's direction as it enters the lower layer (C2). This model represents a simplified, two-layer scenario for acoustic transmission across an ocean boundary with distinct sound-speed characteristics

In the layered model, the acoustic ray path in each layer is described by the circular equation (5). To determine the position of the ray meeting the interface between two layers, it is necessary to find the intersection of the trajectory with the interface at depth z = z_i.

Substituting the value z = z_i into (5), yields a quadratic equation in the horizontal coordinate x:

$$(x-x_0)^2+(z_i-z_0)^2=R^2 \quad (7)$$

Where, z_i depth of the interface.

Solving Equation (7) yields three possible outcomes:

- Two distinct solutions: the ray intersects the interface at two different points. In practice, the physical solution is the one whose horizontal coordinate x is consistent with the ray's direction of travel.
- One repeated solution: the ray is tangent to the interface, corresponding to the phenomenon of total reflection.
- No solution: the ray does not intersect the interface, meaning the ray has reflected in the upper layer before reaching depth z_i

At the valid intersection point, the angle of incidence θ_1 is calculated based on the tangent of the circular ray path:

$$\tan\theta_1=\left.\frac{dz}{dx}\right|_{(xi,zi)} \quad (8)$$

The angle of refraction θ_2 in the subsequent layer is determined by Snell's Law using Formula (6). With the new θ_2 value, the calculation process continues in the next layer until the ray hits the seafloor or reflects back to the water surface.

The procedure described above can be repeated manually (by hand calculation) or executed by computer using a ray-tracing algorithm. Numerical models such as BELLHOP or Gaussian Beam Tracing [15] often utilize the layer-based approach (or stratification method) to simulate complex sound transmission paths in the ocean**.**

4 RESULTS AND DISCUSSION

4.1 Calculation according to option 1 - average time method

In Option 1, the sound propagation time in each water layer is determined using the formula (9):

$$t_i=\frac{h_i}{C_i} \quad (9)$$

Where: - t_i : time of transmission through the i-th water layer

- h_i : thickness of the i-th water layer
- C_i : average sound velocity of the ith water layer

The average time for a sound ray to pass through the entire water column from 10 m to 500 m is determined by formula (10)

$$t_{tb}=\frac{\sum_{i=1}^{n}t_i}{n} \quad (10)$$

with n=13 being the number of water layers from 10 m to 500 m.

The calculation results show that the total sound transmission time through 13 layers is 0.332 seconds. With the average sound velocity in each layer (column 3 of table 1), the sound propagation distance was determined by multiplying the velocity and travel time for each layer ($C_i \times t_{tb}$). Summing the results for all 13 layers yields a total sound travel distance of H_1 =512.717 m.

4.2 Calculation according to option 2 - average velocity method

In Option 2, the acoustic travel distance is determined based on the average sound velocity of the entire water column. The average velocity value from 10 m to 500 m, as shown in Table 1, is 1516.91 m/s. With the total travel time $t_{i_tb} = \frac{500m}{v_{tb}} = \frac{500m}{1516.91m/s} = 0.3296s$, the distance the sound is transmitted is:

$$H_2 = v_{tb} \times t_{i_tb} = 1516.91 \times 0.3296 = 499.974m \quad (11)$$

4.3 Discussion

The detailed results comparing the two calculation methods are presented in Table 2.

Table 2. Comparison of the acoustic transmission path length between the two methods with the theoretical distance of 500 m

Tab 2. Porównanie długości drogi propagacji sygnału akustycznego wyznaczonej dwiema metodami z teoretyczną odległością 500 m.

Calculation method	Sound velocity used (m/s)	Average time (s)	Calculated distance (m)	Theoretical distance (m)	Deviation (m)
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6) =(4)-(5)**
Option 1: Average time method	Each layer (Table 1, column 3)	0.332	512.717	500.000	±12.717
Option 2: Average velocity method	1516.91	0.329	499.974	500.000	±0.026

To evaluate the suitability of each option, first the absolute error compared to the theoretical distance SLT = 500 m is determined by the formula:

$$\Delta S = |S_{tính} - S_{LT}| \quad (12)$$

Option 1 - average time method: S_1 = 512.717 m ⇒ ΔS_1 = 12.717 m

Option 2 - average velocity method: S_2 = 499.974 m ⇒ ΔS_2 = 0.026 m

According to TCVN 10336:2015, compare with the depth error threshold at 95% confidence level based on the TVU formula of IHO S-44 [16]:

$$TVU(d) = \sqrt{a^2 + (b.d)^2} \quad (13)$$

where d is the depth, and a and b are category-dependent parameters. Here, for a depth d=500 m, the threshold for category 3 (corresponding to the typical parameter pair a=1.0 m and b=0.023 m), the Total Vertical Uncertainty (TVU) is ±11,543 m

Compare results according to TCVN 10336:2015

- Option 1: ΔS_1=12.717 m > 11.543 m→ does not meet category 3 (standards) at 500 m depth.
- Option 2: ΔS2=0,026 m≪11,543 m → meets (and exceeds) category 3 standards at 500 m depth.

Compare the results according to TCVN 10337:2015

Showing the depth quality on the chart, corresponding to the data quality category as follows (TCVN 10337:2015, 2015): Category B: ± (1.0 m+2% d) = ±11.0 m at d = 500m. Accordingly:

- Option 1: 12.717 m > 11.0 m → does not meet category B
- Option 2: 0.026 m ≪ 11.0 m → meets category B (very large safety margin)

The results obtained indicate that the stratified seawater environment causes the acoustic ray trajectory to bend according to the sound velocity gradient; modeling using the continuous Snell's Law and the layered approach shows that the transmission path length/time is non-linear with the average velocity. Using the Khanh Hoa–Binh Thuan dataset and comparing against the theoretical path length of 500 m yielded the following results: Option 1 (average time per layer) showed a deviation of +12.717 m; Option 2 (average velocity across the whole water column combined with the measured time of 0.329 seconds) showed a deviation of 0.026 m. Regarding standard comparison: at 500 m depth, option 1 failed to meet the thresholds of TCVN 10336:2015 - category 3 (±11.543 m) and TCVN 10337:2015 - category B (±11.0 m), while option 2 met both (with a large safety margin).

The quantitative results confirm that if the ray-tracing model and measured SSP are not used, the calculation method relying on “average time per layer” can cause a systematic discrepancy of tens of meters at 500 m and does not meet the accuracy standards of current standards. Additionaly, for multibeam echo sounding, SSP-based correction is a prerequisite to ensure data quality for navigational safety, national defense, and socio-economic applications (such as designing channels, ports, and offshore structures).

To enhance the accuracy and sustainability of echo sounding technology under complex and variable marine environmental conditions, some of the following Technical Recommendations need to be implemented:

(i) Measurement and Update: Conduct and update in-situ SSP measurements (using CTD/XBT) by shift and by region; increase the frequency of observation, especially in areas with upwelling or strong seasonal variation

(ii) Ray-tracing Application: Applying ray-tracing throughout the processing chain, performing beam correction, calculating path length/travel time per ray, and converting time-to-distance.

(iii) Error Separation: Establishing and separating the error components caused by sound velocity/ray trajectory; performing cross-lines and independent verification.

(iv) Chart Compilation: Clearly specify the corresponding quality category when compiling nautical charts; for areas with steep SSP gradients (0–300 m), prioritize the thin-layer or continuous model to reduce bias.

(v) Quality Upgrade Preparation: To prepare for data upgrade (above Category 3/ZOC B), it is necessary to set up a denser SSP network, stringent quality control procedures, and standardization of the sound velocity sensor equipment at the transducer.

5 CONCLUSION

The study aimed to establish a theoretical basis and practical procedure for calculating acoustic ray paths in stratified seawater, using Sound Speed Profile (SSP) data from the Khanh Hoa–Binh Thuan region to evaluate depth measurement accuracy under national standards. The ray-tracing approach, based on Snell's law and the layered water column model, was applied. Two calculation methods were compared: (1) layer-wise time-averaged velocity and (2) total mean sound velocity with actual travel time. The obtained results indicated that for a 500 m test, method (1) produced a distance of 512.7 m (error +12.7 m), while method (2) gave 499.97 m (error −0.03 m), satisfying TCVN 10336:2015 and TCVN 10337:2015 standards. The findings highlight that neglecting sound refraction can lead to systematic errors of tens of meters, emphasizing the need to apply actual SSP data and ray-tracing correction. In addition, Limited SSP data at greater depths reduce model reliability; the constant-gradient assumption simplifies real ocean conditions; and field verification under complex environments is still lacking. In the future, enhance SSP measurements in space and time; integrate ray-tracing into multibeam processing; design independent cross-checks for error control; and expand testing across more regions to improve accuracy and standardization.of domestic water.

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Modelowanie toru promienia akustycznego w warstwowej kolumnie wody a dokładność pomiarów głębokości echosondą

Niniejsze badanie analizuje wpływ toru propagacji promienia akustycznego w warstwowym środowisku wody morskiej na dokładność pomiarów głębokości wykonywanych metodą echosondowania w kartografii morskiej. Badanie opiera się na teorii refrakcji akustycznej, stanowiącej ciągłą postać prawa Snelliusa, oraz na modelu profilu prędkości dźwięku w wodzie (Sound Speed Profile – SSP). Opracowano procedurę obliczeniową i korekcyjną opartą na metodzie śledzenia promieni (ray tracing), którą zweryfikowano z wykorzystaniem danych prędkości dźwięku z regionu przybrzeżnego Khánh Hòa–Bình Thuận w Wietnamie. Porównano dwa podejścia do wyznaczania drogi propagacji sygnału akustycznego względem teoretycznej odległości 500 m. Podejście oparte na uśrednionym czasie propagacji w warstwach wody dało wynik 512,717 m (błąd ±12,717 m). Natomiast metoda wykorzystująca średnią prędkość dźwięku dla całej kolumny wody w

połączeniu z rzeczywistym czasem propagacji dała wynik 499,974 m (błąd ±0,026 m). Porównanie z normami krajowymi wykazało, że pierwsze podejście przekracza dopuszczalne wartości określone w normach TCVN 10336:2015 (klasa 3) oraz TCVN 10337:2015 (klasa B), podczas gdy drugie podejście spełnia wymagania obu norm. Wyniki wskazują, że pominięcie refrakcji akustycznej lub modelowania toru promienia może prowadzić do systematycznych błędów głębokości rzędu kilku metrów na głębokości 500 m. Badanie podkreśla znaczenie pozyskiwania danych SSP in situ oraz integracji metod śledzenia promieni w procesie przetwarzania danych z echosond wielowiązkowych w celu zapewnienia wiarygodności mapowania morskiego.

Słowa kluczowe: tor promienia akustycznego; profil prędkości dźwięku (SSP); refrakcja akustyczna; echosondowanie; śledzenie promieni (ray tracing)