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VISUALIZATION PLATFORM FOR OCEAN ACOUSTIC SIMULATION BASED ON MAYAVI

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Abstract: Meteorological navigation data are critical to navigational safety and route planning, but their massive volume imposes a heavy burden on data storage and communication in intelligent shipping systems. Considering the spatiotemporal characteristics of such data and the fact that they allow lossy compression within an acceptable error range, this paper proposes an efficient error-guaranteed lossy compression method for floating-point data. The method modifies the binary representation of mantissa bits within a preset error bound to increase the number of trailing zeros in the XOR results between adjacent values, thereby reducing the meaningful bits that need to be encoded, and selects corresponding encoding strategies according to the resulting XOR patterns. Experimental results on public datasets and real meteorological navigation datasets show that, compared with existing mainstream compression algorithms, the proposed method incurs slightly higher compression time but achieves the highest compression efficiency under the preset error constraints, demonstrating its suitability for scenarios with strict error control requirements in large-scale meteorological navigation data storage and transmission.

Keywords: Mayavi; Volume rendering; Ocean acoustics; Data visualization

1 INTRODUCTION

Underwater detection and communication systems are key components in marine engineering and scientific research, widely used for tasks such as underwater target detection, seabed communication, and marine environmental monitoring. The practical application environments of these systems often face challenges such as complex hydrological conditions, high-cost equipment investment, and uncontrollable risks. In this context, the proposal of a simulation visualization platform becomes an important breakthrough to address these issues. By constructing underwater environment simulation visualization models, users can simulate the acoustic propagation characteristics of real oceans within virtual scenarios. The introduction of simulation technology essentially provides an efficient and controllable platform to overcome the constraints of underwater environments and accelerate the pace of technological development.

Marine acoustics visualization is a research field that transforms marine basic data and ocean acoustic field data into multidimensional dynamic visual images based on the physical laws of acoustics, combined with data modeling and graphics rendering techniques. However, the spatial and temporal variations in water density, temperature, and salinity in underwater environments make the process of sound wave propagation extremely complex, posing significant challenges for visualization simulations. Currently, as society's demand for marine simulations continues to grow, higher requirements are placed on the design and performance of system platforms. To meet social needs and promote the continuous development of marine detection technologies, there is a need to develop a simulation visualization platform. Traditional acoustic field calculation models are limited by single-thread computing modes, resulting in low efficiency and long processing times in scenarios requiring simultaneous multi-angle acoustic field solutions in complex marine environments. In ship navigation scenarios, it is necessary to achieve minute-level response times to support real-time decision-making. Additionally, the platform should adopt a modular architecture design and real-time human-machine interaction mechanisms to create a user-friendly system that aligns with operational workflows.

Therefore, by integrating the Mayavi 3D visualization engine, GIS electronic maps, and parallelized acoustic field calculation models, an efficient and highly interactive marine acoustics simulation visualization platform has been constructed. This platform provides visual decision support for marine acoustics modeling and scientific research validation, possessing significant engineering application value.

2 RELATED WORK

With the growing exploitation of marine resources and increasing global demand for maritime security, underwater detection has become increasingly vital in national defense, marine engineering, and scientific research. As a key research focus in ocean acoustics, underwater acoustic field simulation and visualization has been widely applied in marine exploration, environmental monitoring, and underwater communication, achieving significant technological advancements in recent years.

Internationally, the ray theory established by C S Clay and H Medwin in the 1970s laid the foundation for the study of underwater acoustic propagation. The University of Texas at Austin[1] developed the SEA (Simulation Environment for Acoustics) underwater acoustic simulation tool, which enables high-precision modeling of sound wave propagation characteristics in complex marine media. Michael B. Porter[2] developed the Bellhop acoustic model, which effectively mitigates inaccuracies of traditional models in caustic and shadow zones by integrating the advantages of ray tracing and wave-theoretic approaches. Furthermore, the Underwater Acoustics Technical Committee of the Acoustical Society of America[3] has improved target recognition accuracy in complex environments through multi-sensor data fusion and intelligent algorithms. The University of Tokyo[4] developed Kraken, an underwater acoustic simulation model based on normal mode theory. Kraken effectively simulates underwater sound propagation and scattering phenomena and is typically employed for horizontally stratified media where environmental properties are independent of horizontal range.

Domestically, significant progress has also been made in underwater acoustic field simulation technologies.Yang Jiaxuan et al.[5] utilized the Bellhop model to simulate sound propagation over varying seabed topographies, investigating the influence of seafloor terrain on acoustic transmission.In 2018, Chen Xinning et al.[6] proposed a RAM (Range-Dependent Acoustic Model)-based simulation method for ocean acoustic channel impulse responses, aiming to address the high computational complexity associated with real-time broadband signal simulation involving multiple sensors and targets. Li Meng et al.[7] applied the Bellhop model to simulate underwater acoustic channels and explored detection methods for target sources as well as the relationship between optimal hydrophone array deployment and ray paths. In 2020, Wang Siqi[8] developed an underwater acoustic field simulation system based on the Bellhop model. Additionally, Li Zheng et al.[9] designed and implemented a six-element ocean acoustic positioning simulation system using the MATLAB/Simulink platform, overcoming the high cost and limited flexibility of traditional hardware-dependent acoustic positioning systems.

Scientific visualization originated from computer graphics in the 1960s and was initially used for simple two-dimensional graphical representations. William Lorensen pioneered the Marching Cubes algorithm, which sparked widespread interest in scientific visualization. Numerous algorithms have since been developed to implement volume rendering techniques. Markus and Ljung[10] proposed an image-space ray casting method that enabled global visualization of three-dimensional scalar fields. Tian Liang et al.[11] introduced a footprint-based method in object space and leveraged CUDA parallel computing to optimize this approach, effectively overcoming the limitations of traditional algorithms—namely, high computational cost and low efficiency. Lacroute[12] developed an efficient volume rendering technique based on shear-warp factorization of the view transformation.

3 SYSTEM DESIGN

This paper presents the design and development of a marine acoustics simulation and visualization platform based on Mayavi. The platform is designed to enable three-dimensional visualization of simulated marine acoustic data, thereby providing robust visual support for acoustic field modeling and scientific validation in complex marine environments. Employing a modular architecture, the platform facilitates the extension and updating of its acoustic model library, offering a scalable and extensible technical verification environment for marine acoustics research.

3.1 Architecture of the Marine Acoustics Visualization System

The marine acoustics visualization platform is primarily based on a five-layer architectural design. The architecture of the visualization system is illustrated in Figure 1.

The Application Layer resides at the top of the system architecture and is primarily responsible for handling business logic, functional implementation, and user interaction. It directly responds to business requirements by invoking lower-level services such as the data layer and interface layer to accomplish specific tasks. Its main functions encompass GIS-based route planning, environmental data visualization, and sound propagation data visualization.

The Component Layer achieves high cohesion and low coupling design objectives by decomposing the system into independent functional components. It consists of multiple functional components, primarily including: The 2D Plotting Component is primarily used for interactive display on GIS maps, including content such as propagation loss plan views, propagation loss profile plots, and sound ray trajectory profile plots. It can dynamically display user-required information on the map by employing different 2D visualization techniques tailored to various data types. The 3D Plotting Component supports sound field volume rendering, 3D terrain visualization, and 3D data slicing. It can dynamically display three-dimensional effects of the marine environment based on user interaction, serving to assist the display and interactive control of the main view. The Sound Field Calculation Component enables single-bearing and multi-bearing propagation loss calculations by invoking sound field calculation models. It also supports data interpolation of the calculation results to enhance the smoothness and continuity of subsequent visualizations.

The visualization engine layer serves as the core architectural tier of the visualization system, bearing the crucial functions of data transformation and graphical rendering. This platform achieves efficient rendering by leveraging underlying graphics libraries such as HTML, Mayavi, QcustomPlot and Echarts, supporting both 2D and 3D graphics. Built-in chart components within the libraries include bar charts, scatter plots, heatmaps, topology diagrams, maps, among others, and also support custom component development to meet the requirements of specialized scenarios[13]. It concurrently supports user interactions (such as zooming, dragging, clicking, and box-selecting) and triggers corresponding events—for example, drawing flight routes within a GIS or clicking on a waypoint to display detailed information. During user interaction, the system enables dynamic effects like animated transitions and highlight linkage, thereby enhancing the user experience.

The Interface Layer serves as the central hub for system function orchestration and is designed with three standardized functional modules:

1.Data Management Interface: Provides unified access and management capabilities for multi-source, heterogeneous marine environmental data. It supports the standardized import and dynamic loading of professional data, including terrain profiles, sound speed profiles, seabed sediment parameters, and more.

2.Data Query Interface: Enables querying of various marine data types from marine databases or local .nc (NetCDF) files.

3.Acoustic Field Calculation Interface: Integrates the Bellhop ray-tracing model and the RAM parabolic equation model based on Dynamic Link Library (DLL) technology. Through a parameterized invocation mechanism, it supports calculations for single-azimuth acoustic ray propagation paths and multi-azimuth acoustic field coverage, including propagation loss.

This hierarchical interface architecture ensures module independence while achieving a balance between functional extensibility and computational efficiency for marine environmental data processing, acoustic model computation, and visual representation.

The Data Layer is primarily responsible for integrating and managing multi-dimensional marine environmental data, which mainly consists of four major categories: seabed topographic and geomorphic data, seabed sediment type distribution data, sound speed profile characteristic data, and acoustic field calculation model data. The data primarily originates from publicly available datasets, with the platform acquiring it through external interfaces or by reading local files.

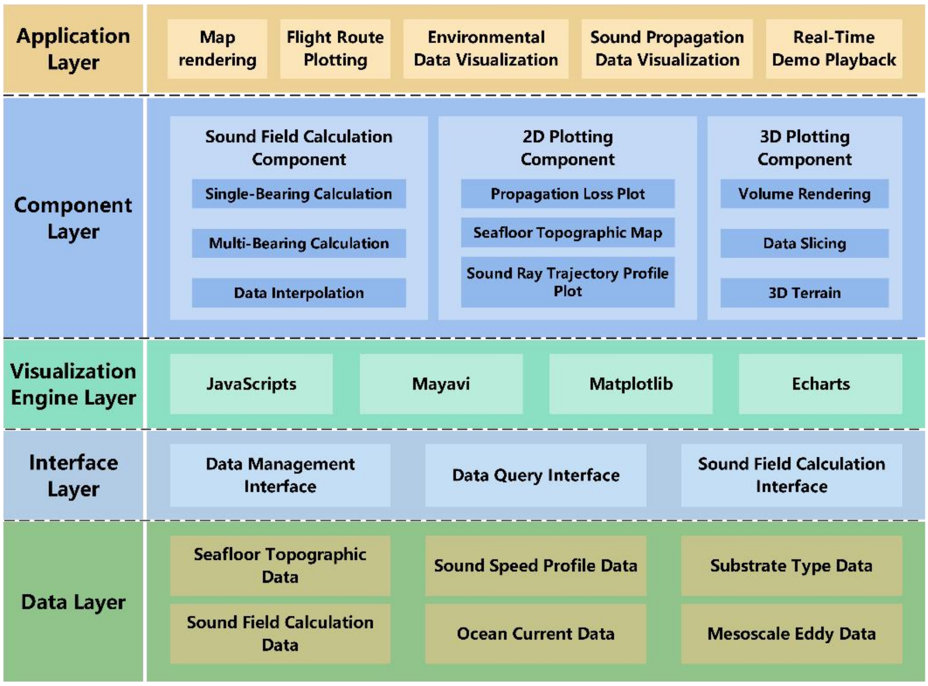


Figure 1 Visualization System Architecture

3.2 Core Function Design

The marine acoustics simulation visualization platform, based on a modular architecture design, implements a complete workflow encompassing marine environmental data integration, acoustic field computation, and interactive visual analysis. The system's functional design covers five core modules (GIS Map Management, Acoustic Field Calculation Management, Environmental Data Management, Environmental Data Visualization, and Acoustic Propagation Data Visualization). These modules are realized through a layered architecture consisting of the Application Layer, Component Layer, Visualization Engine Layer, Interface Layer, and Data Layer, achieving functional decoupling and coordinated operation. The specific functional structure is illustrated in Figure 2.

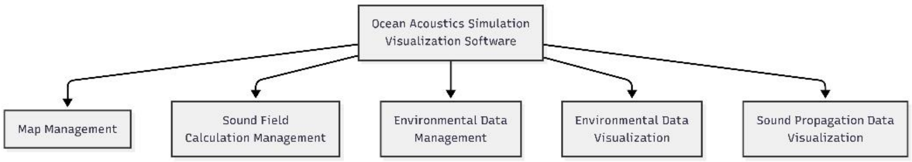


Figure 2 EGFC Encoding Strategy

3.2.1 GIS map management

Map rendering is based on HTML5 front-end technology, utilizing tile data splicing to achieve dynamic map drawing. Tile data is sourced from public TMS tile servers. The acquired target area data is compatible with the Web Mercator projection in Google Earth tile format. By adjusting the Y-axis numbering direction, the data is converted to the OpenStreetMap standard tile structure. The system then uses the PyQt5 QWebEngineView component to load a local Leaflet map page, enabling tile data visualization. JavaScript interaction logic is integrated into the GIS map, supporting latitude-longitude coordinate-based point markers, polyline drawing, and polygon area plotting through coordinate conversion and Leaflet drawing interfaces. The system also includes ship route dynamic simulation functionality. The GIS map is illustrated in Figure 3.

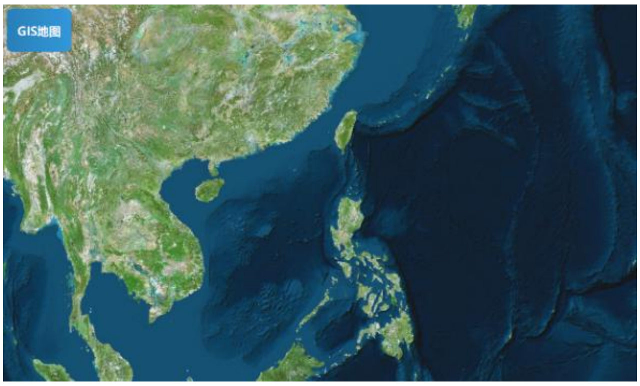


Figure 3 Functional Module Design

Source: Biaozhun Ditu, http://bzdt.ch.mnr.gov.cn/

3.2.2 Acoustic field calculation management

Acoustic field calculation management supports the import of different acoustic models for computation. Currently, it accommodates the parabolic equation model (RAM) and the Gaussian beam ray model (Bellhop)[14]. The models require loading marine environmental data, including seabed topography data, sediment type data, and sound speed profile data, along with input parameters (such as frequency, step size, number of azimuths, etc.) to generate acoustic propagation loss field distribution results.

To address the computational efficiency bottleneck of traditional acoustic field models, a multi-core CPU parallel acceleration approach is adopted, optimizing the serial iterative computation mode into a multi-threaded parallel computation scheme[15]. The acoustic field calculation service employs a process-level parallel acceleration strategy: for each request, an independent process is dynamically created to fully utilize multi-core CPU resources. Furthermore, to further enhance performance, thread-level parallel technology is implemented in conjunction with a CPU affinity mechanism. This mechanism binds specific threads to designated physical CPU cores, allowing them exclusive access to core resources. This binding offers dual advantages: first, it minimizes thread context switching overhead; second, it prevents the operating system from dynamically scheduling threads across different cores, thereby significantly improving CPU cache hit rates. Together, these measures effectively boost overall computational performance.

By pooling CPU computing resources, computational efficiency is further enhanced. The acoustic field calculation service can allocate required resources from the resource pool on demand and, combined with computational caching techniques, achieves high-performance data processing. This approach maximizes the utilization of hardware resources.

3.2.3 Environmental data management

Environmental data encompass multiple marine environmental elements, including seabed topography, sediment types, sound speed profiles, ocean currents, and mesoscale eddies. In the data processing workflow, raw data are stored locally in two standardized file formats: .nc (NetCDF format) and .tif (geographic raster format), and are integrated and parsed through the visualization platform. The NetCDF4 library is utilized to read multidimensional scientific datasets in .nc format, while the GDAL library is employed to parse geographic spatial raster data in .tif format. After parsing, both types of data are uniformly converted into the NumPy array format. Leveraging the robust multidimensional array processing capabilities of the NumPy library, preprocessing operations such as data format standardization, spatial interpolation, and 3D data reconstruction are performed, providing standardized data support for subsequent visualization rendering and spatial analysis.

3.2.4 Environmental data visualization

This module adopts a multi-source data fusion architecture, integrating three foundational layers: Geographic Information System, seabed topography, and seabed sediment properties. The system presents GIS and sediment attribute information in the form of a two-dimensional planar base layer, while simultaneously rendering terrain data in three dimensions to construct a spatially depth-aware topographic model.

For three-dimensional terrain modeling, volume rendering is implemented based on the Mayavi scientific visualization engine. The core technique employs the ray casting algorithm combined with transfer functions for data mapping. The fundamental principle of ray casting involves projecting rays from the viewpoint through the outermost pixels of the image sequence and across the volume data. During this process, the volume data is sampled at intervals. Transfer functions are then applied to assign color and opacity values to each sampling point. Based on a lighting model, these values are accumulated along a fixed direction until the ray traverses the entire volume dataset. The final synthesized opacity and color values correspond to the opacity and color of the pixel projected onto the screen.

The lighting model employed in the ray casting method is the Phong illumination model. Its principle treats ambient light as a constant, and when an object's surface is illuminated by a light source, the reflected light includes not only ambient and diffuse components but also specular reflection[16]. Once the ambient light intensity and the material's specular reflection coefficient are determined, the intensity of the reflected light ultimately perceived by the human eye is related to two angles: one is the angle θ between the incident light direction and the surface normal of the object, and the other is the angle γ between the viewing direction and the reflected light direction. The Phong illumination model can be expressed by Equation 1:

$$I_d=k_a I_a+k_d I_s \cos\theta+k_s I_s(\cos\gamma)^n \tag{1}$$

Where k_s represents the material's specular reflection coefficient, denotes the light intensity from the ambient light component interaction, indicates the light intensity from the diffuse reflection component interaction, is the specular exponent reflecting the surface glossiness of the material, and expresses the light intensity from the specular reflection component interaction.

Furthermore, the system provides interactive visualization controls, allowing users to dynamically switch between two-dimensional planar mode and three-dimensional stereoscopic mode. The three-dimensional view supports 6-degree-of-freedom spatial rotation operations.

For marine current vector field data, the system implements a hybrid 2D/3D visualization scheme. It can present the flow field as a two-dimensional planar vector diagram and also construct a three-dimensional spatial streamline model for ocean currents (as illustrated in Figure 4).

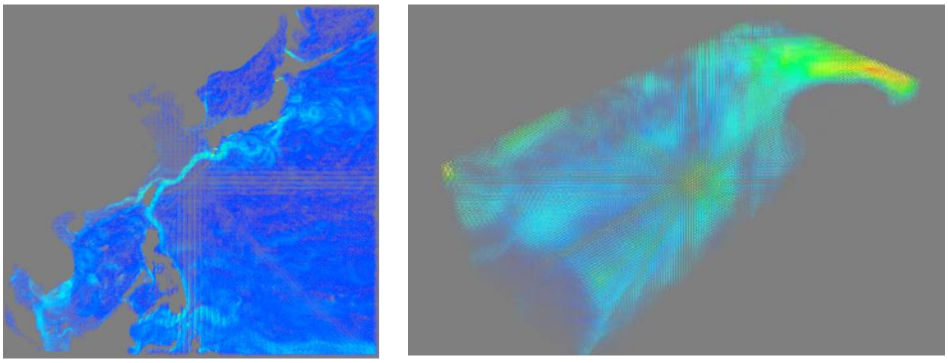


Figure 4 2D Ocean Current and 3D Ocean Current

3.2.5 Acoustic propagation data visualization

For acoustic wave propagation attenuation data obtained from numerical simulations of acoustic field models, multidimensional visualization techniques are employed to spatially represent acoustic field characteristics, including top-down views, profile views, and three-dimensional acoustic field volume rendering.

The 3D acoustic field volume rendering system provides multi-axis slice analysis functionality, supporting three-dimensional orthogonal cross-section operations based on the Cartesian coordinate system. Users can examine acoustic field cross-sections at any depth or select specific angles to obtain attenuation characteristic maps of acoustic fields in particular propagation directions.

To meet the requirements for top-down visualization of acoustic field propagation loss, a segmented linear interpolation method is applied based on discrete azimuth angle data (distributed in eight or sixteen sector divisions) output by the acoustic field model. This method generates continuous acoustic field distributions between adjacent sector boundaries—interpolation is performed every 22.5° for 16-sector data and every 45° for 8-sector data—resulting in a complete acoustic field dataset comprising 360 data points at 1° intervals.

A jet colormap is adopted, with the propagation loss intensity range fixed within [40, 120] dB, This ensures that outliers do not cause chromatic shift in the color scale. A nonlinear color mapping rule is established:

(1) High-intensity regions (≥100 dB) are mapped to dark blue hues;

(2) Medium-intensity regions (70-100 dB) transition through cyan to yellow hues;

(3) Low-intensity regions (≤70 dB) are consistently displayed in red hues.

4 SYSTEM APPLICATION EXAMPLES

4.1 Data Import

The tile map service based on the Leaflet framework must strictly adhere to OpenStreetMap standard specifications, including elements such as zoom levels, coordinate projections, and tile naming conventions. The submarine foundational geographic data layer (including substrate classification, seabed terrain models, and three-dimensional environmental feature data) requires spatial data storage in GeoTIFF format. For the marine dynamic environment data, ocean current field information must be provided in NetCDF format. All data should possess complete spatial reference system definitions and metadata descriptions to ensure spatiotemporal alignment and system compatibility among multi-source heterogeneous data.

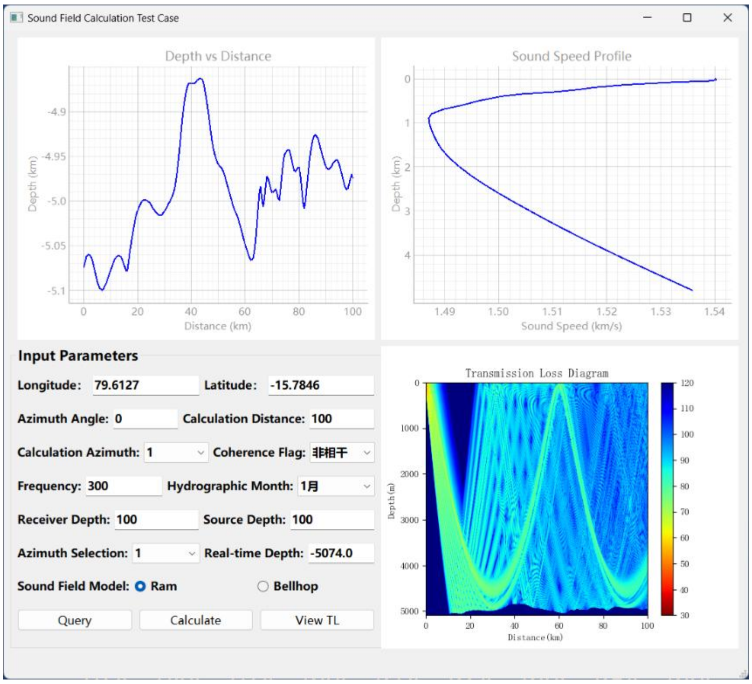
4.2 Model Calculation

This platform integrates both the Bellhop and RAM underwater acoustic propagation models. Users can perform real-time acoustic field simulation calculations for designated sea areas through a visual interface by invoking the acoustic field calculation model to compute propagation loss values at selected locations.

The fundamental principle of the Bellhop model is briefly introduced below. Bellhop calculates the acoustic field in horizontally inhomogeneous environments using the Gaussian Beam Tracing method. The core idea of this method is to assign a Gaussian intensity distribution to each acoustic ray (i.e., the beam centerline). These rays can transition smoothly into shadow zones and pass through caustics with minimal discontinuity, yielding results that more closely approximate wave theory. The central formula of Bellhop is the Gaussian beam acoustic pressure field expression:

$$u(s,n)=A\sqrt{\frac{c(s)}{rq(s)}}\exp(-iw[\tau(s)+\frac{1}{2}\frac{p(s)}{q(s)}n^2]) \tag{2}$$

Where A is an arbitrary constant, $c(s)$ is the sound speed along the ray as a function of arc length s, r is the horizontal range, $q(s)$ is the complex beam curvature parameter, $p(s)$ is the complex beam width parameter, $\tau(s)$ is the travel time integral along the ray, ω is the angular frequency of the sound source, n is the distance perpendicular to the central ray. The interface for acoustic field model calculation is shown in Figure 5.



Input Parameters

Longitude: 79.6127
Latitude: -15.7846
Azimuth Angle: 0
Calculation Distance: 100
Calculation Azimuth: 1
Coherence Flag: 非相干
Frequency: 300
Hydrographic Month: 1月
Receiver Depth: 100
Source Depth: 100
Azimuth Selection: 1
Real-time Depth: -5074.0
Sound Field Model: ● Ram ○ Bellhop

Figure 5 Propagation Loss Calculation in Acoustic Field Models

4.3 Result Visualization

The main interface of the Marine Acoustics Visualization Platform features a GIS map. Within the marine environment scenario, users can load a global marine GIS map through the platform's main interface to quickly locate target sea areas. The GIS map also supports functionalities such as point marking, area plotting, and symbolic annotation to aid in decision-making. Users can obtain marine environmental data for the specified area—including substrate type, sound speed profile, and seabed topography—and render this data in both two-dimensional and three-dimensional forms for visualization. These data simultaneously provide fundamental environmental parameters for subsequent acoustic field calculations.

During the acoustic field model calculation phase, the platform imports the marine environmental data into its built-in acoustic field models for parallel computation, generating acoustic propagation data for the target location. Users can analyze the acoustic propagation loss in the area by selecting from various visualization formats, such as plan view, profile view, and three-dimensional acoustic field volume rendering. As shown in Figure 6, the left side presents a plan view of propagation loss, while the right side displays a three-dimensional acoustic field volume rendering and slicing. Figure 7 illustrates a profile view of propagation loss.

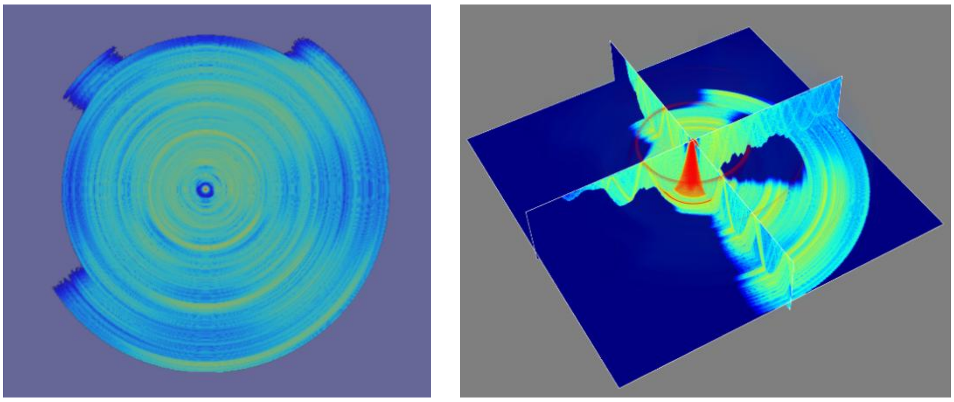


Figure 6 Plan View of Propagation Loss and 3D Acoustic Field Volume Rendering with Slicing

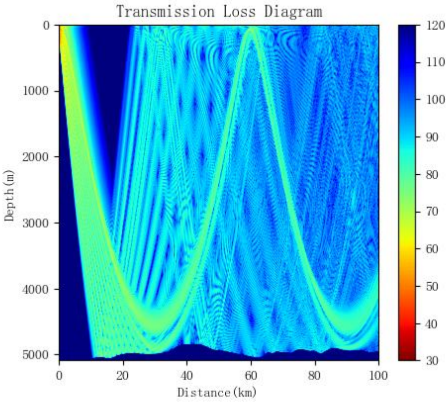


Figure 7 Profile View of Propagation Loss

5 CONCLUSION

Based on the Mayavi scientific visualization engine, this study has developed a marine acoustics simulation visualization platform. By integrating the Bellhop ray-tracing model and the RAM parabolic equation model, and incorporating multi-threaded parallel computing technology, the platform significantly enhances acoustic field simulation efficiency. It effectively addresses the low-efficiency issues associated with traditional single-threaded computational models, enabling real-time dynamic rendering of multi-azimuth acoustic field data.

The platform employs a GIS map and multi-source data fusion architecture, strengthening its capability to represent the spatiotemporal characteristics of marine acoustic data. It supports multi-dimensional coupled analysis of marine environmental data—such as terrain, seabed sediment properties, and sound speed profiles—with acoustic field propagation characteristics. Through interactive 2D/3D visualization techniques, it intuitively reveals the distribution patterns of acoustic fields in complex marine environments. Its modular design supports the extensibility of acoustic models and the dynamic integration of heterogeneous data, laying a flexible foundation for future technological iterations. This provides an efficient tool for underwater acoustic modeling optimization and scientific research decision-making.

Future research will focus on the refined modeling of complex seabed terrain coupling and further enhance the ability to fuse and visualize multi-source heterogeneous data, thereby offering more powerful visual decision support for marine resource exploration.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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