



Design of a Comprehensive Experiment Course for Hydrophone Array-Based Direction Finding and Localization

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Abstract. Traditional experiment teaching often follows a rigid format, leading to a disconnect between theoretical knowledge and engineering practice and failing to effectively cultivate students' systems engineering thinking and comprehensive practical abilities. To better stimulate students' enthusiasm for experiments and enhance their teamwork and engineering skills, this study presents a comprehensive experiment course for hydrophone array-based direction finding and localization. The course takes the typical engineering scenario of underwater target situational awareness as the backdrop and incorporates the theoretical knowledge from Underwater Acoustic Direction Finding and Target Localization. It is structured around four core practical components (i.e., theoretical simulation, equipment operation, a lake test experiment, and capability expansion), aiming to deepen students' understanding of fundamental theories while improving their hands-on innovation skills and awareness. This research contributes to the reform of practical teaching for Underwater Acoustic Direction Finding and Target Localization, as well as the cultivation of high-quality professionals in underwater acoustic engineering.

Keywords: Hydrophone Array; Direction Finding; Practical Teaching

1 Introduction

The ability to detect and localize underwater targets represents a critical milestone on China's path towards a strong maritime country. At present, acoustic waves are the most effective carrier for long-range information underwater, and sonar devices have been widely used for underwater target detection, localization, tracking, and identification. Sonar systems can achieve target direction finding and localization based on underwater acoustic signals [1]-[3], which makes Underwater Acoustic Direction Finding and Target Localization a core component of the college curriculum.

At the authors' university, Underwater Acoustic Direction Finding and Target Localization is one of the mandatory subjects for undergraduates majoring in Underwater Acoustic Engineering and is offered in the spring semester of the third year. It serves

as a crucial bridge connecting professional knowledge with technical practice. In China, research on the practical teaching models for Underwater Acoustic Engineering courses is relatively scarce. Nie et al. and Ma et al. from Harbin Engineering University proposed novel approaches to facilitating industry-education integration and fostering innovation capabilities among postgraduates majoring in Underwater Acoustic Engineering [4][5]. Xu and Zhang introduced free topic selection and discussion in practice classes and reduced the weight of theory examinations from 80% to 60% while increasing the proportion of comprehensive application-oriented questions in the exam to test students' practical abilities [6]. Yin et al. established a virtual simulation platform for detection performance analysis experiments for sonar systems in complex environments [7]. Wu et al. implemented differentiated instruction for the sonar technology curriculum [8]. While practical teaching reform for Underwater Acoustic Engineering is in the exploratory stage, research on the practical teaching of other subjects, such as Communication Technology and Digital Signal Processing, may provide valuable insights and references. For instance, Dong et al. designed a hierarchical experimental teaching system for Emerging Engineering Education [9]. Chou et al. developed an experimental teaching system, which used microcontrollers and wireless communication modules to acquire and process human physiological signals (e.g., ECG, pulse, and respiration), aiming to cultivate applied talents [10]. Wang et al. implemented a series of reform measures for experimental teaching in terms of course content, teaching model, and examination, improving students' practical abilities and innovative awareness in digital signal processing [11].

This study presents a comprehensive practical teaching paradigm for direction finding and localization based on hydrophone arrays, aiming to improve students' perceptual understanding of professional theories and their ability to solve practical problems and to stimulate their learning interest and enthusiasm for participation in experiments. This paradigm aligns the practical engineering applications of acoustic positioning with the theoretical content of Underwater Acoustic Direction Finding and Target Localization, enabling students to fully comprehend and master theoretical knowledge and thus engage in simulation analysis, equipment operation, measurement data validation, and independent exploration with greater enthusiasm. The experimental course starts with theoretical knowledge. A MATLAB simulation experiment is first provided to deepen students' understanding of fundamental principles related to acoustic positioning. Then, a lake test experiment is introduced, where students collaboratively operate hydrophone arrays to collect and validate data using their previously acquired theoretical knowledge. Finally, a challenging capability expansion experiment is designed to simulate practical application scenarios [12], aiming to improve the innovation and practice abilities, theoretical foundations, ability of technology application, professional horizons, and comprehensive competence of students majoring in Underwater Acoustic Engineering.

2 Experiment Design

This experiment course involves four core components: theoretical simulation, equipment operation, a lake test experiment for data validation, and capability expansion. Using practical scenarios as the backdrop, it guides students to gradually accomplish a whole set of learning tasks, thereby helping students comprehend and master the fundamental processes and typical methods of target direction finding and localization, solidify their basic skills in acoustic positioning, and improve their comprehensive practical abilities, independent innovation, and team collaboration awareness. Figure 1 shows the diagram of the experiment design.

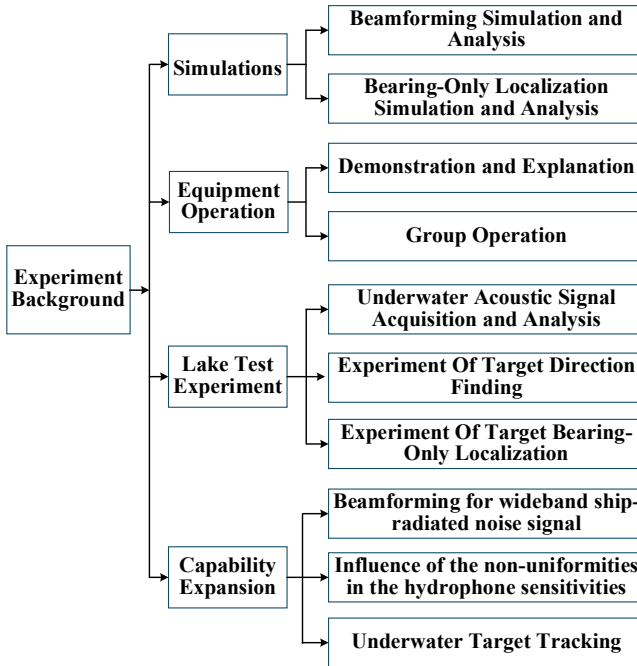


Fig. 1. Experiment Design

- **Experiment Background:** The practical engineering task of passive localization of China's deep-sea manned submersible Fendouzhe (Striver) is introduced as the context to stimulate learning interest and motivation. This section introduces the principles of target direction finding and localization to consolidate students' theoretical knowledge.
- **Theoretical Simulation:** This section focuses on programming and code debugging, providing an opportunity for students to practice their hands-on skills and develop independent innovation awareness. By addressing issues encountered during programming, students can cultivate a rigorous scientific research attitude.
- **Equipment Operation:** The section provides introductions and demonstrations of actual equipment, enabling students to learn about the basic components of the system

and master the fundamental workflow of underwater acoustic signal processing. Also, the team approach can help enhance students' teamwork and communication skills.

- **Lake Test Experiment:** This section requires collaboration. Members work together to complete the experimental tasks, thereby improving teamwork skills, strengthening engineering practice capabilities, and cultivating a meticulous and rigorous scientific outlook.
- **Capability Expansion:** This section emphasizes and is oriented by the actual strategic need of underwater target situational awareness, encouraging students to independently explore beamforming for wideband signals, the influence of the non-uniformities in the hydrophone sensitivities and target tracking based on measured data, thereby enhancing their capacity for independent inquiry.

3 Experiment Structure

In this experiment course, beamforming and bearing-only localization techniques from the course of Underwater Acoustic Direction Finding and Target Localization are basic theoretical content, and simulation analysis and data processing tasks are used to support students' understanding and mastery of the knowledge.

3.1 Beamforming

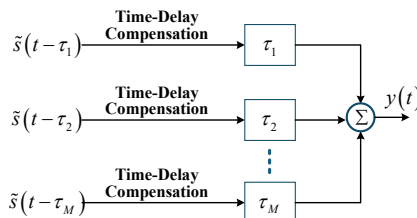


Fig. 2. Time-Delay Beamforming

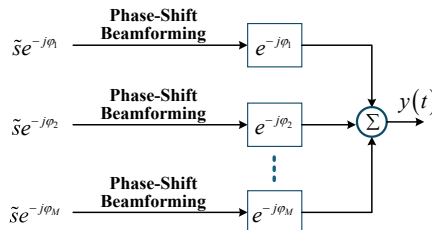


Fig. 3. Phase-Shift Beamforming

Beamforming is achieved by applying phase shifts or time delays to the signals received by each element of a multi-element array in such a way that the incident signals add up

in the desired direction. This can be implemented as either time-delay or phase-shift beamforming, as shown in Figures 2 and 3.

3.2 Bearing-Only Localization

Bearing-only localization uses multiple sub-arrays, each measuring the target's bearing angle. By combining the bearings from two or more sub-arrays, the target's position can be estimated through triangulation and weighted integration, as shown in Figure 4.

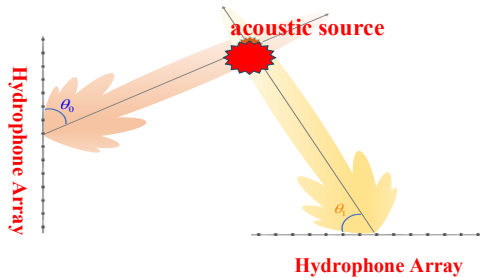


Fig. 4. Bearing-Only Localization

3.3 Target Trajectory Tracking

This capability expansion experiment is expected to encourage students to independently explore the fundamental principles of a range of target trajectory tracking algorithms (e.g., Kalman filtering) and complete experimental analysis and validation using different algorithm strategies.

4 Experiment Content and Conditions

4.1 Experiment Content

The hydrophone array-based direction finding and localization experiment uses practical engineering tasks as the backdrop, aiming to deepen students' understanding of specialized knowledge and underline the importance of theoretical knowledge in practical applications. It achieves the goal of "using theory to guide practice and practice to validate theory".

4.1.1 Theoretical Simulation.

Students select either the phase-shift or time-delay beamforming algorithm to perform the simulation experiment on MATLAB. They analyze the influence of array parameters (e.g., number of elements and element spacing) on beamforming and investigate the problem of left-right ambiguity inherent in line arrays. Moreover, they are required to use the direction finding results to calculate the target's position by virtue of

multi-station bearing-only localization. In summary, this simulation experiment aims to strengthen students' understanding and mastery of theoretical knowledge, preparing them well for subsequent data processing and analysis.

4.1.2 Equipment Operation.

This section provides a detailed introduction to the basic composition and workflow of the hydrophone array used in the experiment. Teachers will demonstrate how to process the signals acquired to obtain desired results, enhancing students' understanding of the fundamental processing method of underwater acoustic signals. Also, emphasis is placed on equipment operation precautions and safety requirements for on-water activities.

4.1.3 Lake Test Experiment.

The lake test experiment seeks to guide students to acquire and process real measurements using the hydrophone array, providing a first-hand experience for them to understand the principles and applications of beamforming. This experiment was conducted in the lake of our university. The lake is approximately 100 meters wide and 200 meters long, with a depth of about 3 meters. The continuous wave (CW) signal at 3 kHz was emitted from a transmitting transducer placed about 1 meter underwater as a target source, and the receiving array consisting of 15 broadband hydrophones was placed approximately 2 meters underwater, where the spacing of the hydrophones is set at 25 cm. Figure 5 shows the equipment layout.

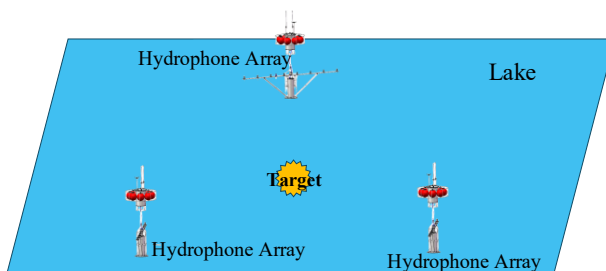


Fig. 5. Equipment Layout of the Lake Test Experiment

- Target Direction Finding and Validation

In this section, students are required to use the data obtained from all 15 channels of the uniformly spaced linear hydrophone array to validate the selected beamforming algorithm for underwater target direction finding, as shown in Figure 6.

In addition, students are required to investigate the following factors using the measured data:

- a. Influence of the Number of Array Elements on Beamforming: Data from seven consecutive channels (e.g., Channels 5 to 11, as shown in Figure 7) are used to repeat the algorithm verification. By comparing the result with the result of the regular 15-

channel scenario, the influence of the number of elements on beamwidth can be determined.

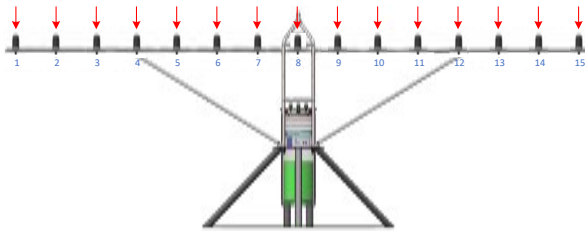


Fig. 6. The Receiving Array Consisting of 15 Broadband Hydrophones

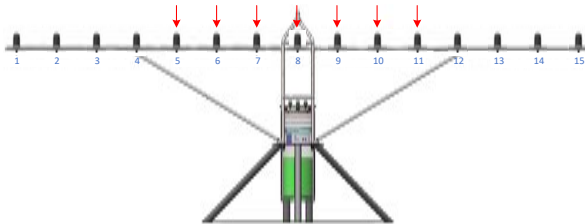


Fig. 7. Selection of Seven Consecutive Channels Data

b. Influence of the Element Spacing on Beamforming: Data from seven non-adjacent channels (e.g., Channels 2, 4, 6, 8, 10, 12, 14, as shown in Figure 8) are used to repeat the algorithm verification. By comparing the result with the result of the regular 15-channel scenario, the influence of the element spacing on beamwidth can be analyzed and verified.

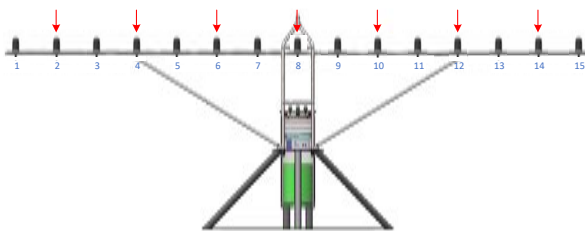


Fig. 8. Selection of Seven Non-adjacent Channels Data

c. Left-Right Ambiguity of the Linear Array: The uniformly spaced linear hydrophone array exhibits directional response only in the horizontal plane rather than the vertical plane. When a beam is formed in the horizontal plane, the left-right ambiguity arises. Specifically, when a beam is formed at a true bearing angle of θ_0 , an identical beam appears on the opposite side. Therefore, if only one target exists at the angle of

θ_0 , the sonar cannot distinguish whether the target is on the left or right side, leading to bearing ambiguity (Figure 9).

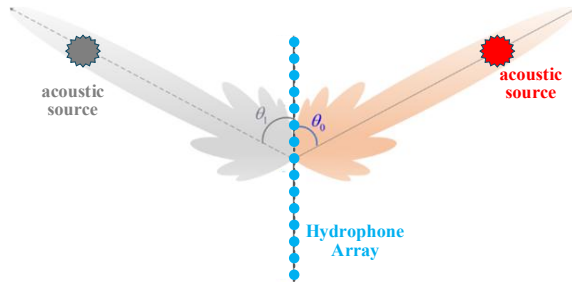


Fig. 9. Left-Right Bearing Ambiguity for the linear hydrophone array

- Multi-Station Localization

The bearing-only localization experiment is designed based on the practical application of underwater positioning for deep-sea submersibles. In this experiment, two or three hydrophone arrays are used, as shown in Figure 4.

4.1.4 Capability Expansion.

Building upon the completion of simulation analysis and data validation for direction finding and localization, higher-order capability expansion experiments are designed to stimulate students' innovation and cultivate their divergent thinking, encouraging them to independently analyze and verify the influence of the non-uniformities in the hydrophone sensitivities on the resulting beam patterns. Additionally, an autonomous underwater vehicle (AUV) is used as the underwater maneuvering target, which could be used to investigate the suitability of the time-delay beamforming method and the phase-shift beamforming method for the wideband ship-radiated noise signal collected by the hydrophone array, and study how to obtain the target tracking trajectory based on the target positioning results in the underwater maneuvering target scenario. Figure 10 displays the result of AUV tracking trajectory.

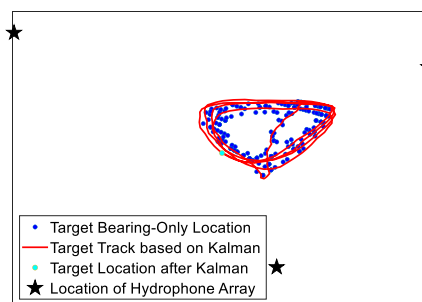


Fig. 10. Experimental result of AUV tracking trajectory based on Kalman

4.2 Experiment Conditions

4.2.1 Site Environment.

The experiments are conducted at the lake at the university. The lake is approximately 100 meters wide, 200 meters long, and 3 meters deep.

4.2.2 Experiment Equipment.

There are three sets of hydrophone arrays and one set of transmitting transducers. The hydrophone arrays are used to receive the 3 kHz CW signal emitted from a transmitting transducer as a target sound source.

4.2.3 Experiment Software.

The programming software is MATLAB, primarily used for performing simulation analysis of array-based direction finding and localization *algorithms*, as well as for reading and processing the measurement data. This experiment course achieves the combination of theory, simulation, and measurement, connecting students' hands-on programming skills with curriculum concepts.

5 Teaching Implementation

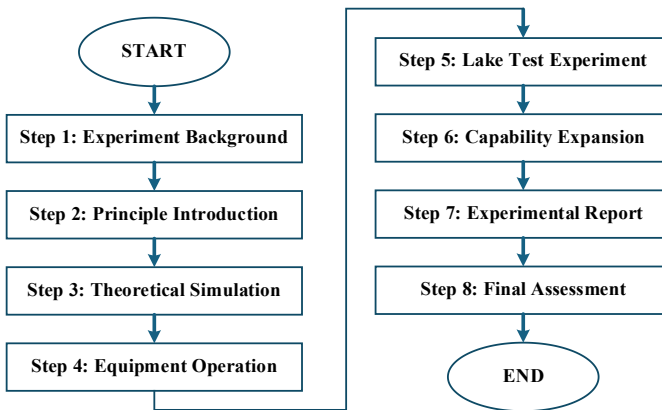


Fig. 11. Teaching Implementation

This experiment course is essentially based on the practical application of underwater target direction finding and localization. Building upon a review of relevant theoretical knowledge, it offers a simulation experiment to help deepen students' understanding and mastery of the knowledge. Teachers use existing laboratory equipment to demonstrate their basic components, workflows, and precautions. Students, working in groups, operate the hydrophone arrays to acquire underwater acoustic signals to complete the lake test experiment and validate the algorithms. Then, students are encouraged to think expansively about target trajectory tracking and independently complete

the experiment report. Finally, teachers are responsible for the comprehensive assessment. The implementation workflow is shown in Figure 11.

Step 1: Experiment Background. The course begins by introducing the real-world engineering challenge of underwater target direction finding and localization. This section covers the experiment's purpose, content, objectives, tasks, and safety precautions, providing students with a foundational overview.

Step 2: Principle Introduction. Instructors provide a concise review of the core principles of time-delay and phase-shift beamforming, as well as multi-station bearing-only localization, to reinforce students' theoretical foundation.

Step 3: Theoretical Simulation. After reviewing the fundamental principles, students independently conduct a beamforming simulation experiment using the hydrophone array. Students should identify factors affecting the direction-finding accuracy and think about increasing the accuracy. Moreover, they are required to simulate a multi-hydrophone array bearing-only localization experiment and analyze the impact of direction-finding accuracy on localization performance.

Step 4: Equipment Operation. Students are divided into groups for hands-on equipment operations. This deepens their understanding and mastery of the compositions, workflows, and precautions of the experiment equipment and helps achieve proficiency in using the hydrophone array.

Step 5: Lake Test Experiment. Firstly, students operate the hydrophone array in groups to read the position and attitude information of the array and collect the underwater acoustic signals. Secondly, students process the measured data from the hydrophone array, validate the effectiveness of the selected direction-finding algorithm, analyze the influence of array parameters (e.g., number of elements and element spacing) on beamforming, and reflect on the left-right ambiguity problem inherent in the linear array. Thirdly, based on the position data of the three hydrophone arrays and the direction-finding results, students validate the multi-station bearing-only localization technique.

Step 6: Capability Expansion. As an advanced exercise, higher-order capability expansion experiments are designed to stimulate students' innovation, such as the investigation of the influence of the non-uniformities in the hydrophone sensitivities on the resulting beam patterns, the suitability of the time-delay beamforming method and the phase-shift beamforming method for the wideband ship-radiated noise signal, and the method of maneuvering target tracking.

Step 7: Experimental Report. Based on the experiment data and results, students independently complete the experimental report. While experiment results may be shared among group members, the result analysis and summary sections must be completed independently. The report should include the experiment purpose, experiment equipment, experiment content, experiment principles, experiment procedure, and experiment summary.

Step 8: Final Assessment. This experiment course employs a comprehensive assessment of the preparation report, MATLAB codes, experiment results, and final summary report, with a total score of 100 points. Specifically, the Preparation Report accounts for 25%, the Experiment Process and Results account for 40%, and the Experimental Report accounts for 35%. Table 1 shows the criteria for assessment.

Table 1. Assessment Criteria

Content	Criteria			
	Excellent	Good	Fair	Poor
Preparation Report	Feasible plan, reasonable schedule (22-25 points)	Relatively clear plan, basically reasonable schedule (16-21 points)	Plan is not very specific, schedule basically reasonable (10-15 points)	Infeasible plan, unreasonable schedule (0-14 points)
Experiment Process and Results	Standardized codes, correct results (35-40 points)	Relatively standardized codes, correct results (29-34 points)	Non-standardized codes, correct results (21-28 points)	Non-standardized codes, incorrect results (0-20 points)
Experiment Report	Standard format, clear expression, thorough analysis, correct conclusions (31-35 points)	Relatively standard format, relatively clear expression, relatively thorough analysis, basically correct conclusions (25-30 points)	Format not sufficiently standard, expression not sufficiently clear, analysis not sufficiently thorough, conclusions basically correct (15-24 points)	Non-standard format, unclear expression, insufficient analysis, incorrect conclusions (0-14 points)

- Preparation Report: Upon understanding the experiment course's content and requirements, students, in groups of three, are required to negotiate and select a direction finding and localization method. This section emphasizes the mastery of basic theoretical knowledge, project design skills, and coordination abilities of students.
- Experiment Process and Results: Students use MATLAB to process and analyze the measured data from the hydrophone array, while teachers examine the project completion. This section focuses on students' engineering practice abilities.
- Experiment Report: As mentioned, although experiment data and results can be shared among group members, students are required to write the experiment report independently, which should include the problems encountered during the experiment and the solutions. This section primarily assesses students' analytical and summary abilities, enhancing their ability to write technical reports.

6 Conclusion

Taking the practical engineering mission of underwater target direction finding and localization as the backdrop, this experiment course utilizes the hydrophone array to demonstrate the application of theoretical knowledge in real engineering. It introduces a sophisticated engineering case to stimulate students' learning interest and participation enthusiasm. Through an approach integrating abstract knowledge with hands-on operation, theory with practice, scientific education with industrial engineering, the experiment course balances knowledge validation and practical application, consolidating students' understanding and mastery of direction finding and localization principles.

Students are allowed to use existing hydrophone arrays at the university to independently complete simulation experiments on MATLAB and validate the direction-finding algorithms based on measured data. This helps cultivate their abilities to discover, propose, and solve problems, and foster a rigorous scientific research attitude. Meanwhile, group cooperation throughout enhances students' teamwork spirit. Finally, the advanced experiment of underwater target situational awareness encourages students to independently study the influence of the non-uniformities in the hydrophone sensitivities on beamforming, the suitability of the time-delay beamforming method and the phase-shift beamforming method for the wideband ship-radiated noise signal, and explore ideas for target trajectory tracking, nurturing innovative thinking and awareness.

This experiment course comprises a full suite of tasks that contribute to students' practical and innovative abilities. It would enhance the capacity to apply learned knowledge to analyze and solve practical problems. Meanwhile, the serious and rigorous scientific attitude and the spirit of teamwork could be cultivated. Positive teaching outcomes have been achieved. Besides the course of Underwater Acoustic Direction Finding and Target Positioning, it would contribute to the reform of practical teaching for courses in underwater acoustic engineering (e.g., underwater acoustic communication systems) and other courses with an engineering application background (e.g., Digital Signal Processing, Communication Principles), which would have significant reference value for improving the quality of professional personnel training.

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