Introduction to the special issue on three-dimensional underwater acoustics

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I. INTRODUCTION

This special issue focuses on compelling three-dimensional (3D) volumetric and boundary effects on underwater sound propagation and scattering in complex and time-varying (thus four-dimensional) underwater environments. It consists of 24 papers covering analytical, numerical, and experimental studies and presents a collection of up-to-date research on this active and relevant topic.

Underwater 3D acoustic effects caused by reflection, refraction, diffraction, and/or scattering of sound energy in both vertical and horizontal planes have been observed and investigated extensively for many decades. A textbook by Lee and Schultz (1995) and a review article by Tolstoy (1996) provided an excellent summary of 3D acoustic research and different modeling techniques up to the 1990s. The research on 3D effects continued in the following years, and many efficient and effective numerical models were developed, e.g., Smith (1999), Sturm and Fawcett (2003), and Heaney and Campbell (2016). In addition, experimental evidence of 3D propagation was also shown, e.g., Frank et al. (2005), Heaney and Murray (2009), and Lynch et al. (2010). The readers are referred to the citations of these listed papers for complete references.

Many physical oceanographic and marine geological features can cause significant 3D acoustic effects. To capture the most profound features for analyzing the underlying propagation and scattering physics, many idealized benchmark problems were proposed, the most important of which is the 3D wedge problem studied by Bradley and Hudimac (1970), Buckingham (1987), Deane and Buckingham (1993), and others. In this special issue, Lee et al. (2019a,b), Lin (2019), Petrov and Petrov (2019), Porter (2019), and Sagers and

Ballard (2019) utilize the 3D wedge problem to demonstrate and verify numerical and scale models. In addition to the wedge problem, other idealized cases that study waveguide parameter sensitivity and ambient noise distribution and correlation can be found in this issue. These include Gaussian-shaped canyons (Barclay and Lin, 2019; Lee et al., 2019b), double seamounts (Porter, 2019), curved nonlinear internal wave ducts (Milone et al., 2019), circular slopes (Katsnelson and Petrov, 2019), and slope fronts (DeCourcy et al., 2019).

Besides idealized cases, many papers in this special issue consider realistic environments, such as estuaries (Reeder and Lin, 2019) and lakes (Sagers et al., 2019), the Hudson Canyon (Ballard and Sagers, 2019; Barclay and Lin, 2019), the East China Sea (Porter, 2019), nonlinear internal waves (Dossot et al., 2019; Duda et al., 2019), the continental slope (Dall'Osto, 2019), the Mid-Atlantic Ridge (Oliveira and Lin, 2019), the abyssal seafloor (Stephen et al., 2019), and even bubble nets produced by foraging humpback whales (Qing et al., 2019). These studies indeed provide useful insights to the understanding of 3D acoustic effects observed in the real world, such as time-varying features caused by salt wedges in estuaries and nonlinear internal waves in the continental shelf area, as well as bathymetric effects on 3D focusing, defocusing, and diffraction.

The ability of numerical models to generate accurate predictions of 3D acoustic propagation and scattering is also highlighted in this special issue. These models include finite-element methods by Qing et al. (2019) to calculate acoustic pressure and particle motion induced by foraging whale vocalizations inside the bubble net, and by Lecoulant et al. (2019) to calculate seismo-acoustic propagation in the ocean and seabed generated by earthquakes. Another group of numerical models uses the parabolic-equation method, which was first introduced to underwater acoustics by Hardin and Tappert (1973) and Tappert (1974). Papers by

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Ivansson (2019), Lee *et al.* (2019a,b), and Lin (2019) focus on handling higher-order cross terms resulting from the square-root Helmholtz operator splitting, while Lin (2019) discusses using a boundary-fitted grid to better handle boundary effects. Also for 3D sound propagation modeling, Porter (2019) extends the beam tracing method and demonstrates its 3D capability with several benchmark problems and a realistic East China Sea example. To improve the prediction accuracy of sound propagation within realistic internal waves, Duda *et al.* (2019) introduce a joint modeling framework to incorporate a nonlinear internal wave model nested in a tide-inclusive data-assimilating regional model. There are three scattering models presented in this issue, including a fully explicit marching-on-in-time scheme to solve the time domain Kirchhoff integral equation by Chen *et al.* (2019), the transient equivalent source method for broadband scattering computations by Fahnline (2019), and a numerical Green's function method to calculate the far-field scattering from objects resting on or buried within the sea floor by Gunderson *et al.* (2019).

Two scale-model tank experiments for 3D sound propagation and scattering by Ballard and Sagers (2019) and Sagers and Ballard (2019) are reported in this issue. With well-controlled laboratory environments and repetitive samples, these tank studies produce high quality data to validate numerical computations. In addition to tank experiments, this issue has papers on real-world data and field experiments, including (1) acoustic data sets collected during the Shallow Water 2006 experiment showing 3D sound propagation effects of nonlinear internal waves (Dossot *et al.*, 2019), and the T-phase wave propagation of a submarine earthquake from the Southern Mid-Atlantic Ridge to the New-Jersey Continental Shelf (Oliveira and Lin, 2019), (2) a 3D sound propagation experiment at the Columbia River estuary for studying acoustic effects of estuarine salt wedges (Reeder and Lin, 2019), (3) the observational evidence of out-of-plane ambient noise in Lake Travis (Sagers *et al.*, 2019), and (4) the Ocean Bottom Seismometer Augmentation in the North Pacific Experiment showing 3D bottom diffraction on the abyssal seafloor (Stephen *et al.*, 2019). Besides the physical effects, the 3D acoustic impacts on source localization and signal processing have long been recognized and shown in experimental data (e.g., Ballard, 2013). In this special issue, Dall'Osto (2019) employs hydroacoustic data collected by the global International Monitoring System of the Comprehensive Nuclear-Test-Ban Treaty Organization to demonstrate how 3D propagation features can be used in source triangulation on a basin scale.

Finally, as Guest Editors, we would like to express our sincere appreciation to the JASA editorial staff for their assistance in producing this special issue. We would also like to thank the Editor-in-Chief, James Lynch, for his encouragement, guidance, and advice. Our thanks also go to the reviewers and Associate Editors who reviewed the papers and provided valuable comments for improvement. Most importantly, we would like to extend our appreciation to all of the special issue authors who contributed high quality manuscripts that clearly display and demonstrate the breadth of the ongoing 3D acoustic research.

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