Stochastic Dynamically Orthogonal Modeling and Bayesian Learning for Underwater Acoustic Propagation

by

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Submitted to the Department of Mechanical Engineering and
Center for Computational Science & Engineering
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in Mechanical Engineering and Computational Science

at the

Massachusetts Institute of Technology

September 2023

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Abstract

Sound waves are critical for a variety of underwater applications including communication, navigation, echo-sounding, environmental monitoring, and marine biology research. However, the incomplete knowledge of the ocean environment and acoustic parameters makes reliable acoustic predictions challenging. This is due to the sparse and heterogeneous data, as well as to the complex ocean physics and acoustics dynamics, multiscale interactions, and large dimensions. There are thus several sources of uncertainty in acoustic predictions. They include the ocean current, temperature, salinity, pressure, density, and sound speed fields, the bottom topography and seabed fields, the sources and receivers properties, and finally the model equations themselves. The goals of this thesis are to address these challenges. Specifically, we: (1) obtain, solve, and verify differential equations for efficient probabilistic underwater acoustic modeling in uncertain environments; (2) develop theory and implement algorithms for the Bayesian nonlinear inference and learning of the ocean, bathymetry, seabed, and acoustic fields and parameters using sparse data; and (3) demonstrate the new methodologies in a range of underwater acoustic applications and real sea experiments, showcasing new capabilities and leading to improved understanding.

In the first part, we derive, discretize, implement, and verify stochastic differential equations that (i) capture dominant input uncertainties in the environment (e.g., ocean, bathymetry, and seabed) and in the acoustic parameters (e.g. source location, frequency, and bandwidth), and (ii) predict the acoustic pressure fields and their probability distributions, respecting the nonlinear governing equations and non-Gaussian statistics. Starting from the acoustic Parabolic Equation (PE), we develop Dynamically Orthogonal (DO) differential equations for range-optimal acoustic uncertainty quantification. Using DO expansions for the input uncertainties, we develop the reduced-order DO-PEs theory for the Narrow-Angle PE (NAPE) and Padé Wide-Angle PE (WAPE) stochastic partial differential equations (PDEs). We verify the discretized DO-PEs in new stochastic range-independent and range-dependent test cases, and demonstrate their advantages over state-of-the-art methods for uncertainty quantification and wave propagation in random media. Results show that a single DO-PE simulation can accurately predict stochastic range-dependent acoustic fields and their full non-Gaussian probability distributions, with computational savings of several orders of magnitude when compared to direct Monte Carlo methods.

In the second part, we extend recent nonlinear Bayesian data assimilation (DA) to the inference and learning of ocean-bathymetry-seabed-acoustic fields and parameters using sparse acoustic and oceanographic data. We combine the acoustic DO-PEs with Gaussian mixture models (GMMs) to predict probability densities in the DO subspace, allowing for efficient non-Gaussian estimation of state variables, parameters, and model functions themselves. The joint multidisciplinary estimation is enabled by state augmentation where the ocean-acoustic-bathymetry-seabed states and parameters are fit together to GMMs within the DO subspace. The new GMM-DO ocean acoustic inference system is validated by assimilating sparse data to infer the source depth, source frequency, and acoustic and environment fields and parameters in five new high-dimensional inference test cases based on state-of-the-art oceanographic and geoacoustic benchmarks. We evaluate the convergence to inference parameters and quantify the learning skill. Results show that our PDE-based Bayesian learning successfully captures non-Gaussian statistics and acoustic ambiguities. Using Bayes' law, it provides accurate probability distributions for the multivariate quantities and enables principled learning from noisy, sparse, and indirect data.

In the final part, we integrate our acoustic DO-PEs and GMM-DO frameworks with the MSEAS primitive equation ocean modeling system to enable unprecedented probabilistic forecasting and learning of ocean physics and acoustic pressure and transmission loss (TL) fields, accounting for uncertainties in the ocean, acoustics, bathymetry, and seabed fields. We demonstrate the use of this system for low to mid-frequency propagation with real ocean data assimilation in three regions. The first sea experiment takes place in the western Mediterranean Sea where we showcase the system's performance in predicting ocean and acoustic probability densities, and assimilating sparse TL and sound speed data for joint ocean physics-acoustics-source depth inversion in deep ocean conditions with steep ridges. In the second application, we simulate stochastic acoustic propagation in Massachusetts Bay around Stellwagen Bank and use our GMM-DO Bayesian inference system to assimilate TL data for acoustic and source depth inversion in shallow dynamics with strong internal waves. Finally, in the third experiment in the New York Bight, we employ our system as a novel probabilistic approach for broadband acoustic modeling and inversion. Overall, our results mark significant progress toward end-to-end ocean-acoustic systems for new ocean exploration and management, risk analysis, and advanced operations.

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Acknowledgments

There are a countless number of people to whom I owe a great deal of gratitude for their support during the course of my graduate studies at MIT.

I would like to thank my thesis advisor, Professor Pierre F.J. Lermusiaux, who has truly been an amazing mentor during my years at MIT's Multidisciplinary Simulation, Estimation, and Assimilation Systems (MSEAS) Lab. I am very grateful for all the opportunities he has given me to pursue my research and teaching interests, share my work at several conferences, and learn from his expertise. His guidance during my time at MSEAS has prepared me to tackle research challenges and allowed me to explore new avenues of research, learn valuable research and teaching skills, and contribute to the scientific community. Thank you, Pierre; I truly could not have asked for a better advisor, mentor, and teacher.

I am also immensely grateful for the support of my committee members Professor Henrik Schmidt, Professor Andone Lavery, and Professor Omar Knio. They have provided me with valuable guidance in my research projects and continuous encouragement while pushing me to think outside the box. I feel privileged to have learned from these world-renowned scientists. Thank you Professor Schmidt for all your contributions to the field of ocean acoustics. Your research work, course notes, and computational ocean acoustics book have been crucial resources that I have revisited frequently throughout my work. Thank you Professor Lavery for your incredible support, encouragement, and expertise. Your research work on acoustic scattering and propagation in random media provided amazing references that helped guide the work developed throughout this thesis. Thank you Professor Knio for being a role model and for your vast expertise in Uncertainty Quantification and Bayesian inference. Your mentorship and enthusiasm continue to inspire and guide my approach to science.

I am much indebted to the MSEAS wizards: Dr. Patrick Haley Jr., and Dr. Chris Mirabito, without whom much of this research would not have been possible. Pat and Chris, thank you for all your helpful suggestions and for patiently answering all my questions over the years. I will always fondly remember our interactions during the real-time sea experiments. Thank you for all your help keeping the MSEAS cluster, and students, up and running.

I owe many thanks to our administrative staff: Lisa Maxwell, Kate Nelson, Leslie Regan, Una Sheehan, and Saana McDaniel, for taking many burdens off our shoulders and taking care of us before our deadlines.

I am also thankful to my collaborators: Aaron Charous, Manmeet Bhabra, and the MIT Lincoln Lab Advanced Undersea Systems and Technology Group for the fruitful discussions, signal processing expertise, the tank and ocean array data collections, and the motivation and help in developing the algorithms for the high-resolution acoustic seafloor mapping work in Chapter 6. I would also like to thank Yoland Gao, Corbin Foucart, and Mohamad Merhi for their collaboration in developing the 2DSeaVizKit and 3DSeaVizKit interactive visualization tools discussed in Chapter 7.

This thesis work would not have been possible without the generous support of the Office of Naval Research and the MIT Lincoln Laboratory. We are grateful to the Office of Naval Research for support under grant N00014-19-1-2664 – Task Force Ocean, Dynamic Environmental Estimation, Prediction, and Acoustic Inference (DEEP-AI), and under grant N00014-19-1-2693 – Interdisciplinary Nonlinear Bayesian Data Assimilation (IN-BDA). We are grateful to the Technology Office at MIT Lincoln Laboratory for support under the grant Wide Area Ocean Floor Mapping (Wide-Area). We are also very grateful to the Defense Advanced Research Projects Agency (DARPA) for support under grant N66001-16-C-4003 – Positioning System for Deep Ocean Navigation - Precision Ocean Interrogation, Navigation, and Timing (POSYDON-POINT) at the start of this work.

Academically, I am especially grateful to MIT and WHOI Professors Ahmed Ghoniem, Gareth McKinley, Julien Bonnel, Qiqi Wang, Steven Johnson, Triantaphyllos Akylas, and Youssef Marzouk for their teaching. From the American University of Beirut, I would like to thank Professors Alain Shihadeh, Farouk Abi Khuzam, Ibrahim Abou Faycal, Issam Lakkis, Jack Nurpetlian, Louay Bazzi, Marwan Darwish, and Mutasem Shehadeh. Thank you, in particular, to Professor Issam Lakkis for his incredible mentorship and for always fostering critical thinking. My choice to pursue research in computational engineering and to apply to MIT was largely due to my time spent in his Thermodynamics, Fluid Mechanics, MEMS, and Microfluidics classes as well as working with him at AUB.

To my colleagues in the MSEAS lab, thank you. You have been instrumental to my personal and academic growth during my time at MIT. I will always cherish the memories we have shared. Abhinav Gupta, Aditya Ghodgaonkar, Aditya K. Saravanakumar, Ali Daher, Alonso V. Rodriguez, Aman Jalan, Anantha Narayanan Suresh Babu, Chinmay Kulkarni, Clara Dahill, Corbin Foucart, Deepak Subramani, Ellery Rajagopal, Florian Feppon, Jacob Heuss, Jing Lin, Johnathan Vo, Kyprianos Gkirgkis, Manan Doshi, Manmeet Singh Bhabra, Marcos Botto Tornielli, Michael Humara, Mohamad Merhi, Tony Ryu, Yoland Gao, and Zach Duguid, I am grateful for your brilliance, support, and friendship.

I am blessed with an extraordinary group of friends who have been there for me throughout my time at MIT, cheering me up on my tough days and celebrating with me every success. From MIT, thank you Arkopal Dutt, Andrew Wang, Omar Kahil, Saviz Mowlavi, and Usman Munir for the countless research discussions, fun outings, and for your endless support and encouragement. I will always cherish our friendship. To the Lebanese, Arab, and Muslim communities at MIT, thank you for always being there for me. Finally, to my Boston family, thank you Hussein Hazimeh, Rasha Atwi, Ali Saab, Ali Ayoub, Hadi Salman, Alaa Selman, Kareem Kassem, Aya Kassem, Hiba Kobeissi, Mohammad Hadi, Rola Dbouk, Mohammad Ali Mousa, Maryam Ibrahim, and Diala Lteif, for being my family away from home. To Samia Sabrawi, thank you for your incredible warmth and kindness. From the delicious meals you've prepared to the thoughtful conversations we've shared, every moment spent in your company has been a gift. Your willingness to open your home and heart to us is a testament to the wonderful person you are.

To the Moore, da Silva, and Webster families, I want to express my heartfelt gratitude for the incredible support you've provided me throughout my PhD journey. Your unwavering belief in me has been a driving force, and I am deeply thankful for your presence in my life. To Sophie, Chloe, Nancy, and Rob, thank you for your constant encouragement and warm hospitality. To Oma, your words of wisdom and genuine interest in my academic pursuits have meant a lot to me. To Colleen & Nick, Caroline, and Fiona, your warmth, kindness, and support have made me feel like a part of the family, and I'm grateful for the bond we've built. To Michael and Monique, thank you for all your guidance and advice. Your belief in me during moments of self-doubt and your celebratory cheers during milestones have meant the world to me. I am profoundly thankful for your warm embrace that welcomed me into your family. As I reflect on my journey, I am reminded time and again of the pivotal role you've played. Your support has not only enabled my achievements but has also shaped my perspective on family and the power of standing together through life's endeavors. Lastly, and most importantly, thank you for teaching me how to fish!

Finally, I am at a loss for words to truly convey the depth of my appreciation for my extended family in Lebanon, my grandparents, my parents, Diana and Raif, as well as my sister Dima. Their constant support, guidance, sacrifices, and love have meant the world to me. To my partner Molly, your presence by my side has provided me with strength, comfort, and a sense of belonging like no other. Your patience, understanding, and the way you've always been there to listen, have made all the difference. Your love and support have been my rock, and I'm truly fortunate to have you in my life. Thank you for being my biggest cheerleader and my source of inspiration. I look forward to many more shared adventures and cherished moments together.

In a final word, I turn to my mother, Diana, and partner, Molly, who have been my torch of guidance, inspiration, and motivation: thank you Mama and Molly for having faith in me even when I had lost faith in myself; this thesis is dedicated to you.