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Seafloor identification in sonar imagery via simulations of Helmholtz equations and discrete optimization

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ABSTRACT

We present a multiscale approach for identifying features in ocean beds by solving inverse problems in high frequency seafloor acoustics. The setting is based on Sound Navigation And Ranging (SONAR) imaging used in scientific, commercial, and military applications. The forward model incorporates multiscale simulations, by coupling Helmholtz equations and geometrical optics for a wide range of spatial scales in the seafloor geometry. This allows for detailed recovery of seafloor parameters including material type. Simulated backscattered data is generated using numerical microlocal analysis techniques. In order to lower the computational cost of the large-scale simulations in the inversion process, we take advantage of a pre-computed library of representative acoustic responses from various seafloor parameterizations.

1. Introduction

The acquisition and interpretation of high resolution imagery of the ocean beds is needed in a wide range of oceanographic applications, for example the classification of marine habitats, sediment composition, and detection of naval mines, just to name a few [33]. Acoustic systems that penetrate seawater, such as sidescan sonar systems, are primarily used in underwater imaging [9]. Due to recent advancements in the resolution and speed of acquisition [21], high quality sonar data is increasingly available. This has motivated much scientific effort in developing quantitative methods for extracting details about the seafloor from the measured acoustic response.

Most methods for material classification or object identification using sonar data fall into one of two categories. In the first category, statistical models of the seafloor are developed, often from empirical training datasets [8,12,15,17,23], and used in combination with image processing based methods for classification of texture, geometric and spectral features [14,38]. Matched field processing is a parameter estimation technique for discriminating between the desired signal and incoherence using a-priori knowledge of the environment [2,37]. These techniques are successful in object detection, however they often produce significantly more false detections than the number of true targets [21]. The second category involves determining parameters in physical models of underwater acoustic wave propagation by matching the data with predictions. For example, in [11,39], a library of representative acoustic responses is formed using computer simulations of Helmholtz equations and a label is assigned to regions within the image based on the best fit in the library. In general, the theory and

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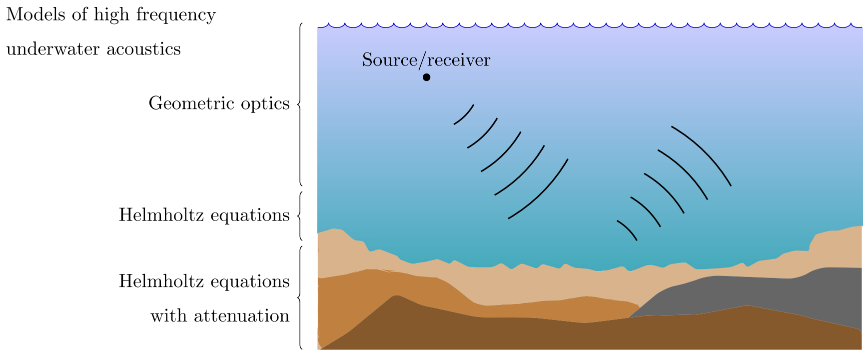

Fig. 1. Wave propagation in an underwater acoustic environment consisting of a water layer and sedimentary layers. In the water layer far from the seafloor, direct ray tracing formulas can be used to approximate the traveling waves. Scattering effects close to the seafloor require accurate simulations of Helmholtz equations.

simulations are well-documented for models in low frequency acoustics [18,23]. Towards the high frequency range, most models and methods are restricted to small spatial domains.

The resolution of these images is determined by many factors, including the bandwidth of source signal, the distance between the source array and the target, and the motion estimate of source and receivers. Understanding the high frequency response from the seafloor is essential to producing high quality images and solving problems of material classification and target identification. It is therefore important to tackle the inverse problem with accurate modeling and simulation of the entire physical wave propagation and scattering process governed by Helmholtz equations. Though there are plenty of fast Helmholtz solvers available, simulations on large domains are still cost-prohibitive.

By taking advantage of the separation in scales between high frequency acoustic wavelengths and large spatial domains, the full scattering process can be broken down into separate stages. As depicted in Fig. 1, an acoustic signal emitted from the source array travels toward the ocean bottom, generating scattered signals as a result of interactions with the seabed. The reverberations are recorded by an array of receivers near the surface and used to create sonar images. There are three main stages: (a) the incoming wave from the source to the sea floor; (b) thin surface layer scattering; and (c) scattering wave propagation toward the receivers. In the high frequency range, stages (a) and (c) are relatively easy to model. It should be noted that variable wave propagation velocity in the water can easily be handled by geometrical optics. For example, direct ray tracing formulas involving the attenuation rate, the distance from the source to the scattering surface, as well as the distance between the surface and the receivers, can be used to model the pressure waves far from the seafloor [19,25]. In [27,28] a careful study is carried out that confirms a fast ray model for accurately simulating source-target and target-receiver propagation when the scattering field near the target is known.

In comparison, stage (b) is much more complex and difficult to handle. Accurate simulation near the sea floor is one of the main challenges in the field because the scattering properties are influenced by a wide range of factors. For example, what are the acoustic parameters, such as wavelength and incoming angle? Does the sea floor consist primarily of clay, sand, sea grass, or rock? What is the surface geometry, especially on the scale that might produce high interference with the incoming waves? Among all the parameters involved in the sonar model, some are given by the problem setup, for example, the acoustic wavelength and incident angle of the source ping. Other parameters are more difficult to obtain, and in fact, determining these parameters is often the main goal in many applications. Here, we aim to provide methods for identifying seabed properties, such as material type, using the recorded backscattered signal. This problem is a typical inverse problem that is often solved using many simulations of backscatter models repetitively in an iterative procedure.

One main challenge is the large computational cost associated with high frequency scattering models. Usually this is addressed by simplifying the forward models, for example, some studies assume a smooth seafloor (as shown in Fig. 2) and approximate the scattered rays by just following the theory of geometric optics with empirical formulas for diffuse reflections [22,26,31]. These simplified models usually provide inadequate descriptions of the complex scattering physics caused by spatially varying material types and microtopography of the sediment layer. Also, in applications such as marine archeology and mine detection, the targeted objects are submerged, and simple surface scattering approximations are not valid [21,29]. There are also practical challenges that influence the modeling. For example, due to the placement of sources and receivers, typical sonar systems record data only in the backscattered direction, which is not necessarily the strongest scattering direction. The weak response is at a higher risk for noise corruption.

This paper provides a different methodology for material classification and object identification, taking these concerns into consideration. The relevant physics is captured by wave theory models combined with a novel technique for determining backscatter, and inversion is performed by incorporating accurate and efficient simulations. More precisely, we assemble a library of acoustic templates representing backscatter from seafloors with varying geometric and geoacoustic parameters. Templates are created using fine scale simulations of Helmholtz equations, pre-computed offline, on partitioned small subdomains of a thin layer near the sea floor. The library is used for material classification and object identification, which