The sound of sediments: acoustic sensing in uncertain environments
van Leijen, A.V.

Link to publication

Citation for published version (APA):
van Leijen, A. V. (2010). The sound of sediments: acoustic sensing in uncertain environments

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: http://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.
Chapter 1

Introduction

One could say that the ocean depths are the final frontier of our planet. As human beings we appear to enter this inaccessible vicinity by exception only. There is a strange attraction that draws humankind to the depths, adventurers in search of arcane creatures or hidden treasure. And much there is to be found...

The continental shelf conceals many natural resources. The offshore industry undertakes a global search for hydrocarbons, such as oil and natural gas reserves. In some places the seafloor is dredged for sand, to raise artificial islands, like off the coast of Dubai. In the North Sea, the sea bottom has become the foundation for wind farms - and potentially for an airport, in the event that Schiphol gets decided to be re-located at sea. All this human activity requires dedicated instrumentation to assess the character of the seabed.

For military operations, uncertainties about the environmental situation could have a major impact on the command and control of naval forces. Mission planning and decision making on the course of action demand awareness of the coverage of available sensors. The dominant sensor for the underwater domain is sonar, a form of acoustic sensing. To assess the performance of sonar, knowledge is required about the sensor system, the target and the present and future state of the environment.

The environmental information that has an effect on sonar performance is twofold. One part concerns ambient noise, and is connected to wind, rain, marine life, distant shipping, and so forth. The other part concerns the propagation of underwater sound, and involves acoustic properties of the water column, water surface and the sea bottom. Most of these properties can be measured or obtained from historical databases, but things are more complicated with the sea bottom.
1.1 Sea bottom characterization

For the exterior of the sea bottom, various instrumentation exists. Remote sensing with satellites can provide low to medium resolution images as in figure 1.1. Modern hydrographic sensors include multi beam echo sounders (MBES) to construct high resolution depth charts, and side scan sonar (SSS) for acoustic imaging of the sea floor. A recent example of the use of SSS imaging is the search for debris of a crashed aircraft (June 2009).

Figure 1.1: The exterior of the Saba bank as imaged with a Landsat satellite, southwest of Saba island. (Source: Millennium coral reefs landsat archive, NASA, http://oceancolor.gsfc.nasa.gov/cgi/landsat.pl)

There is no direct method to measure the interior of the sea bottom. An extensive campaign of seismic profiling might produce an image of separate layers in the sea bottom, but does not uncover the character of various sediments. Taking grab samples or cores is often not possible or of limited value for the application at hand.

An indirect method to obtain sea bottom properties is called geoacoustic inversion. Many scientific experiments with this technique involve a range of equipment. High power and low frequency sonar transmissions are used to penetrate the sea
1.2. Geoacoustic inversion

A geoacoustic inversion technique basically analyses bottom-reflected sound to assess acoustic properties of the sea bottom, such as density and sound speed.

1.2.1 Research challenges

Conventional experiments with geoacoustic inversion usually involve a wide range of equipment to produce and receive underwater sound. The most important tools for inversion are sonar transmitters, numerous hydrophones, and synchronized recorders for data acquisition. As a scientific technique, geoacoustic inversion is a proven method, but for an operational system there are some problematic issues.

For a good assessment of geoacoustic properties, the underwater sounds used need to penetrate deep into the sea bottom. This can be achieved by using sonar transmissions of high power and low frequency, like below 2 kHz. Because of the weight of the equipment and the energy consumption of prolonged transmissions, it is customary to transmit from a mothership. For military applications this can be a problem, particularly when the environmental assessment involves denied areas or covert operations. Another issue with sonar transmissions concerns underwater noise pollution. Marine mammals are known to be vulnerable to loud underwater sounds [110, 99, 95]. And even if sea life has been taken into consideration, e.g., with appropriate mitigation measures [11], the attention of environmentalist groups can be an unwanted side effect to the use of sonar transmitters.

The influence of noise is a sonar problem that can be reduced by using many receivers. Therefore a dense receiver array might contain 32 hydrophones, or more. For application in a remote sensing concept, e.g., with many drifters, the acoustic data need to be transmitted wirelessly. The issue then is that a dense array might produce more data than the available bandwidth permits to transmit.

Once the data have been gathered at sea, parameters of a model of the sea floor can be found in the lab with inversion techniques. The result of such an analysis
could be a layered model of the sea bottom, which describes acoustic properties such as density, attenuation and sound speed for the various layers. The inverse process is based on repeated evaluations of simulated propagation of underwater sound [126]. Therefore the method usually takes a long time, sometimes days or more which is not very efficient, when information is needed about the accuracy of the obtained model of the environment. The improvement of both efficiency and accuracy is investigated in chapter 7 with a careful comparison of metaheuristic optimization techniques.

1.2.2 Research questions

Based on the challenges that come with geoacoustic inversion techniques, the following research questions have been formulated:

1. What alternatives are there for the use of sonar transmissions in geoacoustic inversion, and more particularly, how can shipping sound be used as a sound source of opportunity?

2. How can the large volume of acoustic data that is required for geoacoustic inversion be controlled, and what are reasonable proportions for an operational system?

3. How can the accuracy of inverted models of the sea bottom be assessed?

4. When an inverse problem is given, how does one select and configure a metaheuristic optimizer for the best performance of the inverse process?

The work that is documented in this thesis began as part of the Rapid Environmental Assessment (REA) research project of the Netherlands Defence Academy. The project gave rise to two sea trials: in 2006 on the Saba bank [76] and the Battlespace Preparation trials of 2007 in the Mediterranean Sea [78]. Both trials were supported by the Netherlands Hydrographic Service, which participated with hydrographic survey vessel HNLMS Snellius. To answer the first two questions, the REA project studies the use of shipping sound and sparse receiver arrays. Apart from PhD work of Matthias Meyer on adjoint methodology [88, 89], the last two questions have been researched using metaheuristic optimization schemes.

1.2.3 Methodology

The collected data contain many underwater recordings of platforms such as HNLMS Snellius, NRV Leonardo, the REMUS autonomous underwater vehicle, and recreational boats. Next to the recorded shipping sound, other environmental
measurements have been made that characterize the water column (sound speed profile) and the sea bottom (seismic profiling). The environmental data either support the inverse process, or provides some degree of ground truth for the inverted model of the environment.

The data are analyzed with inverse techniques that are explained in chapter 3. In short, the analysis concerns phases of selection, pre-processing, geoacoustic inversion and uncertainty analysis of the obtained environmental model. At first a selection is made of good or interesting recordings that are documented well enough to enable inversion. The selection also identifies what frequencies and range intervals are useful for inversion. Then with the pre-processing phase, the large volume of selected acoustic recordings for the separate hydrophones is translated and reduced into a number of cross spectral matrices. For each frequency and range between source and receiver, such a matrix correlates the receptions for combinations of individual phones. The phase of geoacoustic inversion then aims to find an environmental model that best explains the observations. And the last phase aims to assess the accuracy of the obtained model by providing posterior probability distributions.

In addition to the acoustic part of an inverse problem, this thesis studies the optimization part of the process. According to literature, various metaheuristic methods have been applied to deal with the optimization part of geoacoustic inversion. To answer the question about the selection and configuration of the best metaheuristic, four methods are compared using measured data. The measures of performance that are used are efficiency and accuracy of the inverse process.

1.3 This thesis

This thesis is based on published (and reviewed) articles of which some are included as separate chapters. To start with a further motivation, chapter 2 [72] provides the military context for research in geoacoustic inversion. The chapter that follows then provides the basics of (geo)acoustic inverse theory and a review of the relevant scientific literature.

1. Chapter four [76] reports on the sea trials that took place on the Saba bank, in 2006. If underwater acoustic sensing is a battle between signals and ambient noise, why not let the ambient noise be the signal? To find out, the self noise of hydrographic survey vessel HNLMS Snellius was received nearby on a sparse vertical array and exploited as a sound source to sense the seabottom. Passive sonar techniques were used to localize the ship, and the ships self noise was effectively used to invert a full geoacoustic model of a layered sea bottom. In addition, an uncertainty assessment was made for the obtained parameters.
Chapter 1. Introduction

2. Chapter five [78] documents a novel concept of geoacoustic inversion with the self noise of an autonomous underwater vehicle (AUV). These programmable platforms are relatively quiet and run below the surface, which makes them ideal sound sources for deployment in a discreet REA campaign. Acoustic data were gathered from a REMUS AUV, during the Battle Space preparation sea trials of 2007. The inversion resulted in a characterization of marine sediments.

3. To study the efficiency and accuracy of inversion schemes, various metaheuristic optimization techniques have been studied. Chapter six [73] documents how Ant Colony Optimization (for the first time) has been applied to geoacoustic inverse problems and further how the method has been used to specify the uncertainty in inversion results.

4. With the various metaheuristic optimizers that have been used in geoacoustic inverse problems, the question for the best performing method is addressed in the seventh chapter [77]. Four metaheuristics are compared: Simulated Annealing, Genetic Algorithms, Ant Colony Optimization and Differential Evolution. After proper tuning of each method it has been observed for two real geoacoustic inverse problems that the efficiencies of the population based metaheuristics are nearly the same. It is therefore concluded that proper tuning is just as important as selection of the most suitable metaheuristic.

1.4 Work not covered in this thesis

During the study of geoacoustic inversion, some work has been done on vector sensors. These sensors not only measure sound pressure and phase, but also yield the acoustic particle velocity. An article about non-linear beam shapes (‘hippoids’), together with prof. dr. Kevin B. Smith from the Naval Postgraduate School in Monterey (USA), was published in the Journal of the Acoustical Society of America [117]. Smith is the author of the MMPE propagation model and during our work on the potential of particle velocity for acoustic inversion [75], we found that there was an error in the model with regard to bottom attenuation. The model has been updated [118, 116] and can be downloaded for free from the Ocean Acoustics Library.

To carry out inversions and compare various methods, the author has written a LOBSTER toolbox [71] (the Low-frequency Observation Based Sonar Toolbox for Environmental Reconstruction). This object-oriented Matlab code interfaces

\[\text{\url{http://oalib.hlsresearch.com/}}, \text{ last visited June 19th 2009}\]
with variants of the KRAKEN [105] and MMPE [115] (third party) propagation models and offers a number of objective functions. For some time now, there has been a free and open source\textsuperscript{2} inversion software package by Gerstoft [38] that goes under the name SAGA. The reason for not using SAGA is that the LOBSTER code supports inversion with acoustic particle velocity [75] and also includes more metaheuristic search strategies. Apart from conventional metaheuristics such as Simulated Annealing and the Genetic Algorithm, implementations of Differential Evolution and Ant Colony Optimization are included.

\textsuperscript{2}http://www.mpl.ucsd.edu/people/gerstoft/saga/saga.html, last visited August 5th 2009