Chapter 2

Operational Context

1990. Somewhere above the Atlantic Ocean a lone maritime patrol aircraft is on a mission of anti-submarine warfare. Directed by intelligence from at the time highly classified sound surveillance systems, the crew is ordered to monitor a designated area with a field of sonobuoys. The first buoy to hit the water is an expendable bathythermograph (XBT). The device samples the temperature profile in the water column and the operator quickly derives a sound speed profile. After the propagation conditions of underwater sound are reviewed for tactical consequences a pattern of sonobuoys is dropped with favorable spacing and depth settings. It does not take long before a contact emerges on one of the outer buoys...

2000. An expeditionary force of various surface ships is about to enter a coastal area. To predict the performance of various acoustic sensors, the water column is sampled with a bathythermograph. Details about the local seabed conditions are unknown and the sonar performance model is then run with global parameters from an environmental database. As a result a mine hunting operation takes twice the time that was actually needed to clear the area of mines because of non-optimal sonar settings. Meanwhile a bottomed submarine remains effectively hidden in the reverberation, waiting for the main force to close in.

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2010. An amphibious force is to land on a beach that has been selected from satellite imagery. A discreet campaign of rapid environmental assessment then reveals the presence of a muddy sediment layer. Mud is ideal sediment for self-burying mines and means that the beach is not accessible for heavy armored vehicles. With this secretly gathered information a new area is selected and the amphibious operation unfolds itself as an unopposed landing.

2.1 Introduction

When expeditionary forces enter shallow or confined waters, the environment has a great influence on the performance of platforms, sensors and weapon systems. For this reason, environmental knowledge is regarded as one of the key factors in making decisions on the course of action and asset allocation [1]. The examples above illustrate how the right level of battlespace information enables effective operational planning and mission execution [96]. For naval oceanography the main objective is to provide forces with a competitive advantage over adversaries by exploiting the current and future state of the environment.

The Royal Netherlands Navy (RNLN) possesses various sensor performance models and tactical decision aids for its combat systems. Many environmental input parameters can be provided in advance by the Netherlands Hydrographical Office (nautical charting) and the METOC office of CODAM (environmental briefing dockets and databases). Some parameters are measured or sampled at sea, such as weather conditions, water temperature and underwater ambient noise. For expeditionary operations it is likely that a priori knowledge about the environment is limited and outdated. Therefore there is a need for tools that enable hydrographers or naval oceanographers embedded with the forces to collect and validate environmental information at sea [7].

2.2 Environmental information for naval warfare

Each mission type has its own operational need for environmental information in terms of data accuracy and spatial and temporal resolution [96].

In Anti-Submarine Warfare (ASW) it is crucial to know how well sonar performs. Environmental information enables the prediction of acoustic detection ranges on submarines and surface ships. For the open oceans, the propagation of sound is foremost determined by properties of the water column, such as temperature and salinity. Shallow waters are often characterized as an unpredictable and complex environment. For sonar, the performance is determined by many factors,
such as tides, currents, wind, rain and reflections from the sea surface and complex bottom structures. The essential data for propagation modeling are often incomplete, and therefore the daily predictions of sonar performance are seldom close to reality. In addition, water conditions and sound speed profiles change during the day due to temperature changes and weather conditions.

Mine Counter Measures (MCM) also depend on various oceanographic factors [98]. The bathymetry (charted water depth) and the acoustic properties of the medium determine how well mine hunting sonar will perform. Acoustic detection of mines is limited by sea bottom reverberation. A rough estimate of the sediment type is sufficient to indicate the underwater visibility and the likelihood of mine burial, but coastal mechanisms of river outflows and sediment transport makes that gathered information gets easily outdated.

In amphibious operations the shallow water bathymetry determines how close to the coast support ships and landing craft can safely get. Important information about the beach, such as trafficability and the slope, can be found with an autonomous underwater vehicle during high tide. In general, the characterization of the sediment and bathymetry for amphibious purposes permit a rough level of detail.

It is easily overlooked that the shallow character of the littorals can also be exploited. A rough approximation of the underwater battlespace is already valuable for a tactical exploitation of the environment (TEE). A submarine can tactically exploit the reverberant properties of the sea bottom or be positioned to benefit from the directionality of ambient noise. TEE concerns easy rules of thumb and needs only rough estimates about the environment, as in “active sonar performs better in down slope direction than up slope”. Environmental knowledge with a high level of detail enables passive source localization with techniques known as Matched Field Processing (MFP). The advantage of MFP over conventional Doppler arithmetic is that the latter requires movement of the target and information about the zero-frequency and MFP does not. On the other hand MFP depends on a propagation model that operates on accurate environmental data. The technical character of MFP further calls for a highly skilled and well-instructed operator.

Various levels of battlespace information can be obtained with a campaign of rapid environmental assessment (REA). The aim is then to measure, analyze and evaluate relevant properties of the environment in order to establish a recognized environmental picture (REP). The intention is that forces have a shared awareness of the battlespace and that they have it in time. Since 2004 the RNLN operates two hydrographic survey vessels HNLMS Snellius and HNLMS Luymes. These modern ships are fitted with an extensive sensor suite for digital charting and further tasks of military hydrography [81]. For covert REA the navy may call upon
Special Forces and submarines of the Walrus class, as was demonstrated during the exercise Joint Caribbean Lion (2006). Like many other navies within NATO, the RNLN is still in transformation from a blue water force to an expeditionary brown water force. Currently not all important environmental data for shallow water operations can (rapidly) be gathered.

2.3 Acoustic sensing in shallow water

The environmental factors that impact acoustic sensing capabilities are manifold. Shallow bathymetry and underwater obstacles may hinder the use of long towed arrays. The presence of divers or marine wildlife may call a halt to mid or low frequency sonar transmissions. Coastal ambient noise includes an abundance of directional sound sources with manmade or natural origins. The focus of this chapter is on those parameters that influence sound propagation, or more specific: the transmission loss due to sea bottom interaction.

The water column is usually characterized by measuring conductivity (to estimate salinity) and temperature as function of depth (CTD sampling). To study the effects on sound propagation according to Snell’s law of refraction [128], a sound speed profile can be derived from these measurements, e.g. using an empirical formula [86]. In deep water the propagation of sound is determined by this profile only; in shallow water many more parameters are involved.

Various definitions can be given for shallow water [130]. From an acoustical point of view shallow water is found “when each ray from the source, when continued long enough is reflected at the bottom” [17]. Another definition is “a water depth in which sound is propagated to a distance by repeated reflections from both surface and source” [128]. To be practical, shallow waters are often said to be on the continental shelf and bordered by the 200 m contour line.

Unlike the water column, the sea bottom cannot rapidly be characterized by insertion of some sampling device. Nevertheless, sound waves easily propagate in and out of marine sediments. Received signals can then be analyzed with geoacoustic inversion techniques to back trace acoustic properties of the ocean bottom from the spatial and temporal structure of sound pressure fields. Experiments for seabed assessment utilize a sound source and a receiver array for a one-time observation at sea of bottom reflected sound. A geoacoustic inversion process is then initiated to find a parametric description of an environmental model in terms of sediment layering properties and geoacoustic parameters such as sound speed, density and attenuation.
2.4 REA as a research project

The Rapid Environmental Assessment (REA) project at the Netherlands Defence Academy aims to understand the nature and impact of environmental conditions on the propagation of sound in shallow waters and sedimentary bottom types [2]. As such, the project aims at the development and validation of acoustic remote sensing systems and inversion methods. The result is a reliable and rapid environmental assessment of shallow water areas in support of various mission types.

A central question in this thesis is: what acoustic information about the seabed can be obtained from bottom-reflected shipping noise? The feasibility of geoacoustic inversion with non-traditional sound sources has been studied with data from two sea trials.

During SABA06, a Caribbean survey of the NL Hydrographic Office (NLHO) in 2006, small-scale experiments in a remote and isolated area were conducted from hydrographic survey vessel HNLMS Snellius [76]. To acquire data and test the concept of inversion with shipping sound, the Snellius served as the sound source. The trials demonstrated a rapid deployment of sensors and equipment and resulted in a well-documented acoustic dataset. A unique achievement is that geoacoustic inversion was performed while the team was on board and an environmental debrief was provided, all within 24 hours.

The BP/MREA07 sea trials of 2007 were a much bigger effort [34]. Together with the NLHO, the NATO Undersea Research Centre (NURC) and various other institutions a shallow water area in the Mediterranean Sea was surveyed with a multitude of sensors. The overall aim of the trials was to demonstrate the concept of naval battlespace preparation by providing a recognized environmental picture (REP). The dynamic and coastal area includes deeper water (200 m), very shallow water (30 - 10 m), a harbor approach and the beach. The multi sensor approach makes it possible to validate results of geoacoustic inversion experiments with nontraditional sound sources under various circumstances.

2.5 Discreet REA

The preparation of some remote coastal area with an overt REA campaign is in obvious conflict with the concealed nature of submarine and amphibious operations. Therefore environmental assessment in support of military operations will often be a discreet endeavor. Covert assessment of the sea bottom calls for clandestine deployment of sound sources and receiving sensors. The REA project studies various ways in which signals with geoacoustic information can be received. Receiving sensors can be inserted in denied areas by acoustic-oceanographic buoys.
2.6 Sound sources of opportunity

For a thorough assessment of bottom properties acoustic signals are required with low frequencies that penetrate deep into the bottom. Shipping sounds are also low, with frequencies from 50 Hz up to 2 kHz. One of the reasons to launch a REA campaign is to aid in the prediction of passive acoustic detection ranges of ships and submarines. The conventional method relies on active sonar transmissions. There are however some practical down sides to the active approach. The high power consumption of low frequency systems limits the endurance of remotely deployed systems such as drifters, buoys and autonomous underwater vehicles [96]. And assessment with loud transmissions and low frequency is also more of an overt approach. An alternative is to utilize sound sources of opportunity. A military motive to do so is that (counter) detection is avoided and environmental assessment can be done in a discreet manner. Another motivation is that the method inflicts a minimal impact on divers and marine wildlife [76].

Coastal waters allow for a high concentration of human activities and as a result shallow waters are a noisy environment. With the right sensors there are many ships that can act as a sound source of opportunity. At some distance from the coast there is merchant traffic in designated shipping lanes, augmented by fishing vessels and offshore suppliers. Closer to the coast there are the ferries and the recreational boats. In times of military conflict various types of naval vessels may patrol coastal waters.
The REA project has lead to geoacoustic inversion with cooperative surface ships, unmanned underwater vehicles and even non-cooperative recreational boats; the platforms are pictured in Fig. 2.1. For the Saba bank, geoacoustic inversion with received shipping noise from HNLMS Snellius revealed a very thin layer (15 cm) of sandy sediment over a subbottom of calcareous rock [76].

The BP/MREA07 sea trials featured experiments with various sound sources of opportunity. When opportunities occurred these sources behaved as planned, as in the experiments with self noise from HMLMS Snellius and NRV Leonardo [34]. During a particular run that focused on the self noise from the relative quiet REMUS AUV [69] there was much interference from the weekend traffic. But then these recreational boats turned out to be fantastic sources of opportunity [70] and demonstrated the strength of the inversion method in using non-cooperative sound sources for a rapid and reliable characterization of the local sediment.

2.7 Applications

2.7.1 Basic acoustic sensing

Underwater acoustic sensing is a battle of the decibel that is about hearing without being heard. Quieting of submarines and increased ambient noise in coastal areas have resulted in a general decrease of acoustic detection ranges in anti-submarine warfare.

For passive sonar in shallow water significant gains are possible when sensors with a vertical aperture are combined with (near) real-time signal processing techniques [97]. Environmentally adaptive algorithms may combine a track-before-detect approach with time-reversal algorithms in order to focus acoustic waves. Coastal ambient noise is highly directional in bearing and azimuth and this is where adaptive beam forming with arrays of directional vector sensors [117] can contribute even more. For passive sonar, environmental adaptive algorithms provide cleaner displays and easier track identification. The potential for active sonar is strong mitigation of reverberation.
For expeditionary missions, relevant oceanographic data are often under sampled in space and time. Therefore, and to further adapt deep-water procedures for the littoral zone, the logical addition to sampling of the water column with expendable bathymetrical thermometers, is to assess seabottom properties with geoacoustic inversion techniques, as the U.S. Naval Oceanographic Office (NAV-OCEANO) already practices [96]. The required resolution and acceptable level of environmental uncertainty depend on the range of mission types that naval forces fulfill.

Significant advances in acoustic sensing are possible, yet they come with a price. Apart from the integration of dedicated shallow water sensors and environmentally adaptive processing, education and operational training remain a key factor. Acoustic sensing has never been easy, and a lack of education can easily degrade sensor performance. But when the skilled hands of a ‘techno sailor’ are provided, major improvements in sonar performance are still possible.

2.7.2 Advanced acoustic sensing

Littoral waters are often said to be a harsh environment for sonar, but the presence of the seabottom can also be a highly beneficial feature. The advanced concept of matched field source localization exploits bottom reflections of underwater sound and has various advantages over basic sonar systems.

- The technique is passive, which means that naval forces can operate covertly.
- In contrast with basic sonar, the technique provides the depth of a contact. Obviously, this is a very important classifier to distinguish a surface vessel from a submerged platform.
- Localization with basic systems of passive sonar is usually the result of target motion analysis (TMA): an extensive effort of analyzing Doppler shift or bearing rates. But considering the shallow water environment and quieting of modern submarines, continuous sensor coverage is something from the past. Matched field processing operates on a single intercept, that can be of a very short duration. The technique even has potential to locate stationary sound sources, such as a bottomed submarine.

Nevertheless, the capabilities of matched field source localization are limited in the absence of proper environmental knowledge. When relevant environmental information is gathered with geoacoustic inversion techniques, matched field processing can be a fast method to find the range and depth of a sonar contact. As an alternative, this dissertation demonstrated to localization of an autonomous underwater vehicle by inversion of both the position and relevant environmental parameters.
To demonstrate the influence of environmental knowledge on matched field source localization, the acoustic intercept of a recreational boat has been studied [70, 72]. Chapter 5 describes an experiment from BP07 of environmental assessment based on geoacoustic inversion with the self noise of an autonomous underwater vehicle. During that experiment there were many recreational boats that left Castiglione della Pescaia. Fig. 2.2 shows how one of these boats is localized with matched field processing for five tones from the inboard diesel engine, and given two different environmental models. When bottom properties from a military environmental database such as ASRAP are used, with a rough spatial resolution, the method fails to correctly identify the source position. MFP with the bottom model from the AUV inversion resulted in Fig. 2.2.b with one clear spot at the surface and 920 m away from the receiver. This example clearly illustrates how proper environmental information enhances acoustic sensing capabilities.

2.7.3 Assessment of buried waste

Ocean dumping of waste is a forbidden activity by international conventions. Nevertheless, there are many dumpsites from the past and marine accidents do still occur, next to the illegal dumping of natural and artificial wastes. Toxic dumpsites are in general not well documented, due to the covert nature of industrial and military dumping operations. An example is found in the Baltic Sea, where according to existing documentation, at least 65,000 tons of toxic chemical munitions have been dumped in the post-World War II years [14]. In an attempt to build instrumentation to assess marine dump sites, various authors [59, 67] have considered geoacoustic inversion as a means to investigate buried waste.

During an acoustic sea trial in the Møja Söderfjärd dumpsite [93], a small box of $1.3 \times 0.3 \times 0.3$ m was positioned half-buried in the seabed. At first, side-scan sonar was used to locate the box with a bottom depth of 75 m. The next step was to use a transmitter that was mounted on an ROV, and to ping the box from nearby with frequencies between 2 kHz and 20 kHz. A separate sparse and vertical receiver array was used to measure the multiple-aspect scattering of the box. The geoacoustic inversion resulted in the acoustic impedance of the contents [60] (density and sound speed), next to range, depth, roll, pitch and yaw of the box.

This application of buried waste assessment deals with a search space of these seven parameters. The performance of the applied global optimization techniques (differential evolution and genetic algorithm) could most likely be improved with the tuning process that is presented in this dissertation.
Figure 2.2: The benefit of environmental information for source localization with matched field processing. Pictured is the mismatch surface for depth and range. The engine noise of the recreational boat should be found just below surface, and is identified with minimal mismatch $\Phi$, denoted with the color black. The upper image (a) is based on uncertain bottom properties drawn from databases such as ASRAP and does not give a clear solution. The lower image (b) based on the covert REA mission with the AUV has one clear (black) detection of the recreational boat at the surface and 920 m from the receiver.
2.8 Conclusions

Naval oceanography is regarded to be a key factor in underwater warfare. Various mission types have their own operational need for environmental information. Since the end of the Cold War, the operational areas have shifted from open ocean towards the littoral zone. The Royal Netherlands Navy has the ambition to support expeditionary operations, that could be executed together with the army or air force (‘joint’) or other nations (‘combined’). Rapid Environmental Assessment is a general concept of gathering timely and relevant environmental information about the area of operation. The proposed use of true sound sources of opportunity, such as ferries, recreational boating or military patrol boats, provides the navy with the capability of discreet rapid environmental assessment of remote and denied areas.

This dissertation aims to find out what acoustic information about the seabed can be obtained from bottom-reflected shipping noise. The feasibility of geoacoustic inversion with non-traditional sound sources has been studied with data from two sea trials. During the experiments on the Saba bank (2006) the concept was demonstrated with a short REA campaign in a remote and isolated area. With the BP07 sea trials in the Mediterranean Sea of 2007, the covert battlespace preparation concept was further experimented with and complemented by a multi-sensor survey of various bottom types and water depths to further validate geoacoustic inversion methods. Before these activities are further reported, the next chapter gives a basic introduction in acoustic inverse theory.