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An assessment of broadband acoustic techniques for determination of sediment parameters

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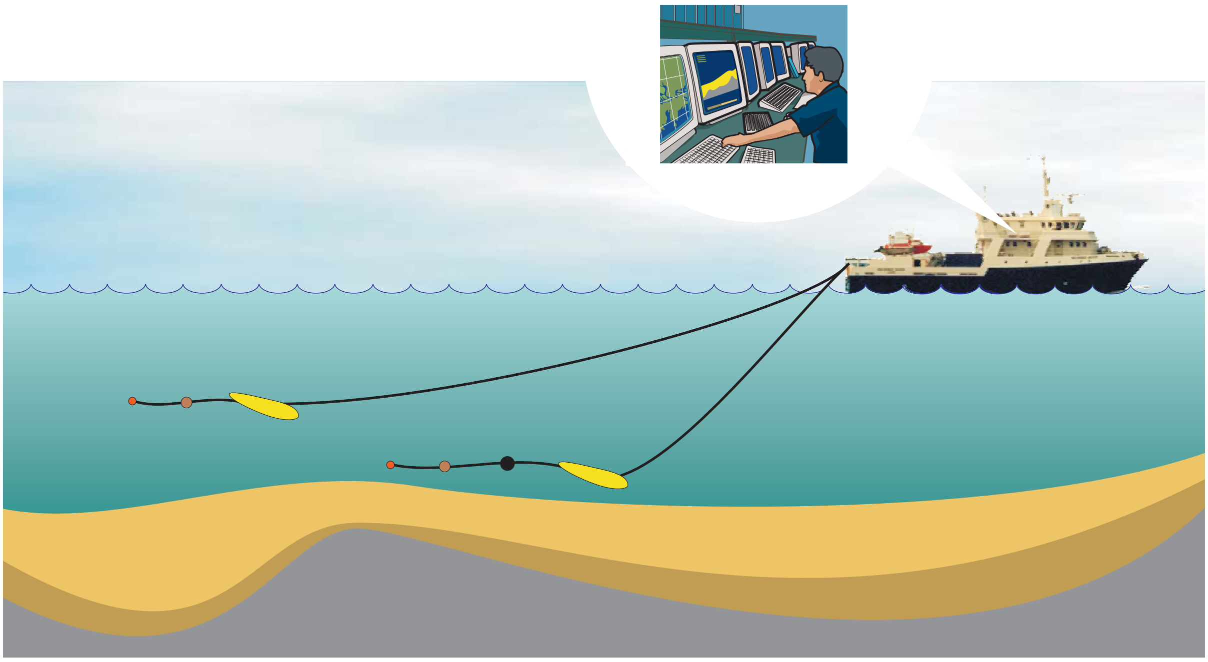

Systems Technology
SE-172 90 Stockholm

SWEDISH DEFENCE RESEARCH AGENCY

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Author/s (editor/s)
Leif Abrahamsson

Project manager
Peter Krylstedt

Approved by
Monica Dahlén

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Leif Abrahamsson

Report title

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Abstract

Predictions of acoustic wave propagation in the sea require knowledge of geoacoustic sediment parameters like sound velocity and absorption. The development of methods for rapid determination of sediment data is a very active research area. This report is a review and an assessment of the state-of-the-art of broadband inversion techniques. For this purpose we study a few field trials, which can be considered as representative of new approaches. A common feature is the matched-field technique, in which measured data are compared to simulated data from wave propagation models driven by hypothesized bottom parameters.

Attention is also paid to recent advances of sub-bottom profilers, which may be equipped by software tools for analysis of reflection data.

Keywords
geoacoustic sediment parameters, sub-bottom profile, matched-field inversion, underwater acoustics

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Rapportens titel

En utvärdering av pulsad akustisk teknik för bestämning av sedimentparametrar

Sammanfattning

Prediktering av ljudvågsutbredning i havsvatten kräver kännedom om geoakustiska parametrar såsom ljudhastighet och absorption. Metodutveckling för att snabbt kunna bestämma sedimentdata är ett mycket aktivt forskningsområde. I denna rapport sammanfattas och utvärderas metoder som bygger på pulsad akustisk teknik. I detta syfte har vi valt ut några fältförsök, som är representativa för nya angreppssätt. Ett gemensamt särdrag är matched-field tekniken där mätdata jämförs med simulerade data från vågutbredningsmodeller som har matats med tänkta bottenparametrar.

Den senaste utvecklingen av sedimentekolod uppmärksammas. Även här används fysikaliska modeller för analys av reflektionsdata.

Nyckelord
geoakustiska sedimentparametrar, sedimentekolodsprofil, matched-field inversion, undervattensakustik

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Contents

1 Introduction

1.1 Geoacoustics of marine sediments

Coastal areas are largely surrounded by shallow seas or continentals shelves with water depths less than 200 m. All merchant and military shipping must pass through these areas when entering or leaving port. The sediments of such waters are of extreme interest in civilian and defence applications. This report deals with a very specific topic of the sub-bottom, namely the determination of geoacoustic parameters such as sound velocity and absorption. These parameters often have a strong impact on the propagation of sound in seawater through acoustic interactions with the bottom.

The geoacoustic parameters must be determined by emitting sound waves in the water and measuring the response of the seabed. Inferring sediment properties from measured data of wave propagation experiments is termed inversion or remote sensing. Direct measurements using sediment grab or core samples is too impractical. These techniques are useful for complementary checks and ground truthing in selected places.

The literature on remote sensing of marine sediments is voluminous. A broad division can be made with respect to the frequency range of interest. Sound waves of low frequency propagate through the sediments, and part of the energy is returned to the water column after reflection at the sediment/bedrock interface. For active sonar systems, which operate at high frequencies (larger than 10 kHz), it is the seafloor itself and its near surface layer, that is the main concern. The acoustics of the surficial part of the sediment, and reverberation due to surface roughness, is not covered by this report. Instead attention is limited to geoacoustic parameters that affect low frequency sound propagation.

So far most inversion studies have been focused on methods using probing signals of one or just a few tones (frequency sounding). However, the interest in inversions of acoustic broadband data is steadily growing, and time-domain approaches are also in progress at FOI. This report is a review, and an assessment of the latest developments of geoacoustic inversion of broadband data. Future trends are presented. Merits and drawbacks of different techniques are discussed.

1.2 FOI member of exclusive club

Large research efforts are spent worldwide on the development of techniques for determining sub-bottom parameters by remote acoustic sensing. Progress in this area is a long-term evolution process involving naval as well as academic research communities. It is a multidisciplinary task in which advances in diverse scientific disciplines as marine geology, wave propagation, signal processing and undersea measurement technology are exploited. The ability to perform inversion studies in marine environments is exclusive, even from an international perspective. Fortunate circumstances have made FOI a significant actor in this field. Recently a number of inversion studies have been carried out at FOI both in underwater acoustics and marine electromagnetics [1],[2], [3],[4],[5],[6], [7],[8].

1.3 A sea with multifaceted sediments

The Baltic Sea is a complicated geoacoustical environment. Near shore the bottom geology can be very irregular with rock outcrops interspersed by varved layers of mud, clay, silt, sand and till. In archipelagic areas the upper part of the seafloor may look like a 3-D mosaic. Occasionally the sediments contain gas, which act as strong acoustic reflectors. Seaward the thickness may amount to 100 m [9]. The acoustic properties of the underlying bedrock may also be of importance, especially where the sediment layers are thin or at very low frequencies.

Unfortunately, only a limited amount of sub-bottom data are available. Yet, they are part of the environmental input to sonar descision systems for prediction of detection ranges, evaluation of sensor performance and naval stealth [10]. In a recent study by Sw AF [11] recommendations were made for a continual update of existing sediment data bases. Although this report is focused on long-term scientific issues, rather than the immediate need of improving the amount and quality of sediment data, due attention is paid to the technical aspects of present acquisition strategies.

2 Seismic reflection surveying

2.1 An ever-lasting technique

Seismic reflection surveying is a classical geophysical technique, which has been practiced since the early 1920's. The power and the range of applications are steadily growing with the advances in computing technology. The scales of resolution and depth of exploration are extremely wide. The target depth may extend to tens of kilometers for geophysical studies of the continental crust and the upper mantle. At the other end of the scale reflection surveying may be applied for high-resolution shallow geology of features less than one meter. The most spectacular success is illustrated by the detailed mappings of hydrocarbon reservoirs at depths of several kilometers [12].

At sea the survey can easily cover large areas as the source and/or the receiver are towed with ship under transit. In marine geology the seismic techniques are broadly divided into vertical profiling, wide-angle reflection and refraction surveying. This terminology is directly related to the main direction of the probing signal, vertical, intermediate or horizontal. The arrival time of an echo is the basic piece of information of the measurements. In vertical profiling with the receiver close to the source a late echo may be due to a thin low-velocity layer or a thick one with high velocity. The velocity-depth ambiguity can be resolved by using phase information of a multitone signal. However a simpler solution is to use two horizontally separated hydrophones. Having two arrival times from two well separated hydrophones enables a determination of both velocity and thickness of a homogeneous and planar layer. The separation distance source-hydrophone (offset) in wide-angle reflection surveys is roughly equal to the depth of exploration. In refraction studies the offset is much larger than the target depth. Refraction surveys are widely used in large-scale stratigraphy to delineate interfaces of different types of rocks. Estimates of geoacoustic parameters of shallow sediments mostly rely on the wide-angle reflection technique.

2.2 Traditional sediment classification

Vertical profiling is the most common survey technique for sediment classification. The seafloor is insonified by a narrow beam near normal incidence. The backreflected signals reveal geological structures as layers of till, sand, clay etc. The underlying, or uncovered, crystalline or sedimentary bedrock may be identified as a strong return. The sub-bottom penetration may reach depths of several hundred meters, although achievable depths are strongly subject to bottom conditions, and the frequency band of the acoustic source. The acoustic instrumentation, a sediment echo sounder or profiler, can be acquired with turn-key features. The acoustic source, and the receiving array, may be hull-mounted or towed. They are operated with ship under way. An acoustic pulse is triggered repetitively with a period that depends on the water depth, and echoes are detected by hydrophones in the vicinity of the source. The recording interval of each shot (ping) is some 0.5 s. The received time-series of pressure (traces) from each shot are displayed one after another in a 2-D graph with time and range as the vertical and horizontal axes. A typical seimic reflection profile is shown in Fig. 1.

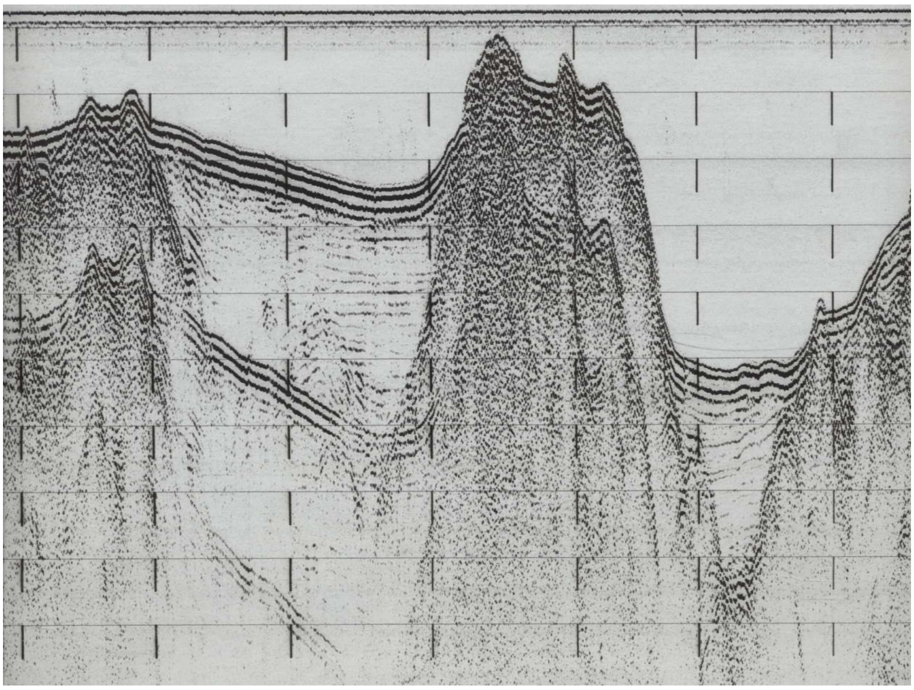

Figure 1: *A seismic reflection profile from the Stockholm archipelago with a rough bathymetry. The vertical axis is two-way travel time with 12.5 ms between horizontal grid lines. The horizontal extent from left to right is around 2.8 km. Deep pockets of Holocene mud are clearly seen between almost uncovered bedrock outcrops. The reoccurring horizons in the middle of the picture are artifacts due to multiple reflections.*

At SGU (Geological Survey of Sweden) reflection data are obtained by a towed airgun-streamer system as well as a bottom penetrating echo sounder with center frequencies around 750 Hz and 3 kHz respectively. The information of both profiles is coordinated with additional observational evidence as archival data from nearby corings, sidescan sonar imagery etc, with the purpose to create sedimentary maps of the sub-bottom

[13], [14]. The geological interpretation is a time consuming task requiring knowledge of glacial depositions, erosion processes, stratigraphy and morphology. After sediment classification, the geoacoustic parameters are determined from table lookups using type values of various sediments. Our present knowledge of geoacoustic sediment parameters are largely derived from profiling surveys performed by SGU and SU (Stockholm University, Department of Geology and Geochemistry).

2.3 The chirp sonar project

Many attempts have been made to extend the structural information from reflection profiles with a direct quantitative analysis, in particular in deriving surface impedance from the initial echo strength. Unfortunately, such efforts have been beset with difficulties related to surface and volume scattering, source-receiver directivity characteristics, frequency dependent impedance and overlapping reflections.

An ambitious venture to develop a quantitative sub-bottom profiler was made at Florida Atlantic University, Boca Raton, FL [15]. The system was termed the chirp sonar due to the great confidence in the emitted pulse, a 10 ms chirp covering the frequency band 2-10 kHz. The chirp pulse is a linearly frequency modulated pulse (LFM) with a large frequency range as well as a large time-bandwidth product. It is compressed at the receiver by a matched filter that correlates the chirp return with a replica of the outgoing pulse. The temporal resolution after compression is approximately equal to the inverse of the bandwidth. The corresponding spatial resolution of the chirp sonar is around 10 cm. The wide bandwidth also improves the beam pattern by smearing of the sidelobes.

Both the transducer and the receiving line array were mounted in a towfish designed for profiling at ship speeds varying from 0 (drifting) to 10 kn. The impedance of the seafloor, and the attenuation coefficient as a function of depth, were to be determined in real time with ship under way. The impedance was estimated by measuring the amplitude of the first arrival. The reflection loss was obtained from calibration data using known types of seafloor, after which the impedance can be computed. The impedance, being a product of velocity and density, can be resolved into its constituents using an approximate correlation formula of velocity and density.

Much work was spent on determining sediment attenuation. Assuming that the logarithm of attenuation is a linear function of both frequency and the distance travelled by the pulse as commonly done, it can be shown that the center frequency of the returned chirp pulse is less than the emitted one. This phenomenon can be quantified and measured. By sliding a time-window down the measured trace the spectral content can be monitored, which in turn is used to estimate the absorption as function of depth.

Sea trials of the chirp sonar were done in Narraganset Bay, RI, and Kiel Bay, Germany [15],[16]. The experimental results were validated by core data.

2.4 Technology adopted by industry

After the development of the chirp sonar as a research tool, the technology was adopted by several marine engineering companies and today sub-bottom profilers are even commercialized as Chirps. Recent advances have included aids for sediment classification [17],[18]. In particular the determination of a depth dependent attenuation coefficient directly from the measured traces can be used to determine type of sediment by using table lookups in the reversed order. However, calibration of signal characteristics of ground truth is needed at the beginning of each survey. A fully automated interpretation process is still far from being implemented as standard. It requires more sophisticated physical-based models, in particular Kirchhoff scattering theory [19],[20] for bottom roughness and impedance estimates.

2.5 The v35 experiment

The drawback of vertical profiling is the difficulty of resolving the velocity-depth ambiguity. However, measurements of arrival times of echoes from at least two well separated hydrophones makes it possible to determine both velocities and thicknesses of planar layers. An example of this approach is described next.

This experiment was conducted by FOI in the Stockholm Archipelago in August 2002 [5]. The purpose was to determine the velocity, density and the absorption of the sediment by the wide-angle reflection technique. The transmitter and two hydrophones were deployed on the seabottom with the offsets 23 and 45 m respectively. The water depth at the site was 22.5 m. A vertical section of the geometry is shown in Fig. 2.

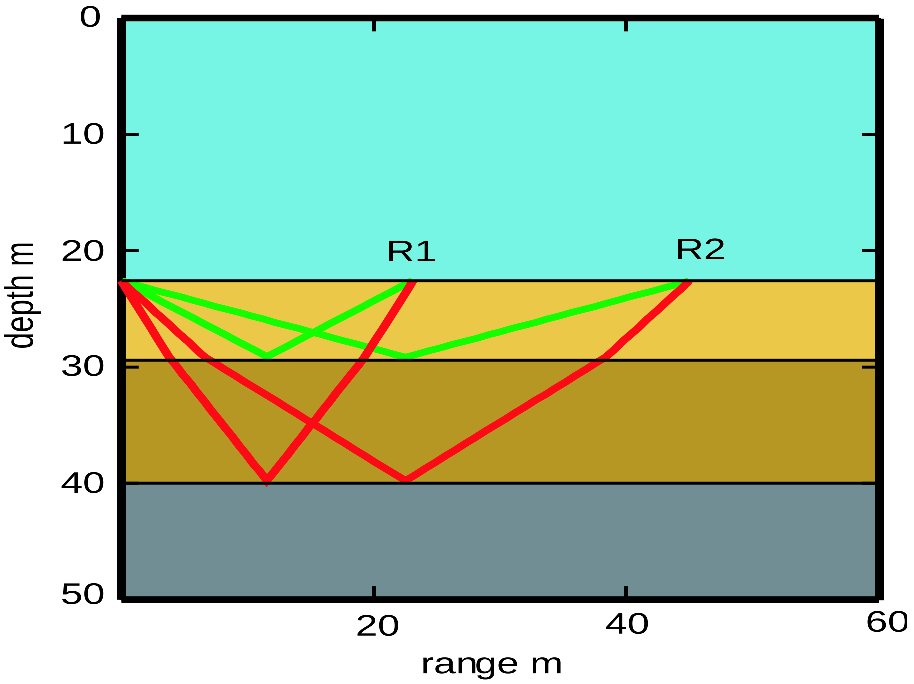

Figure 2: *Eigenrays traversing one sediment (green) and two sediments (red) with source and receivers (R1 and R2) on the seafloor.*

The emitted signals were Ricker pulses centered at the frequencies 0.5, 1, 2 and 4 kHz. The result of the inversion analysis can be summarized as follows. The seabed was found to concist of two sediments on top of a strong reflector, probably bedrock at a depth of 40 m. The thickness and the average sound velocity of the top sediment were estimated to 7 m and 1425 m/s respectively and the deep sediment to 11 m and 1664 m/s. They were determined solely by identifying four arrival times, two at each receiver, of pulses travelled along the ray paths depicted in Fig. 2. The density and absorption of the two layers were determined by means of measured amplitudes of waves having traveled along specfic ray paths. The low-frequency pulses were most useful for inversion of the deep sediment.

When both the source and receiver are located on the interface of two different media, then the sound energy emitted horizontally along the direct path, splits in the far-field into two lateral waves whose velocities are equal to those on each side of the interface. The lateral wave having travelled in the top sediment could be observed in the recordings of the present experiment. From its arrival time it was inferred that the surficial velocity of the top sediment was 1390 m/s, which was less than the sound velocity 1444 m/s of the water at the bottom.

3 Matched field inversion in the time-domain

3.1 A simple yet powerful idea

The essence of matched field inversion is to compare data from computer simulations with measured data. The simulations are supposed to reproduce the outcome of the experiment by modeling of the physical processes, in this case acoustic or elastic wave propagation. The model must be run by the same signal as being used in the experiment. It requires the use of controlled sources with known characteristics. In addition, environmental data is needed as input, including bottom parameters. The latter are unknown and the target of the inversion. This difficulty is circumvented by making a guess of bottom parameters. The computational model can now be run with hypothesized bottom parameters. If there is a mismatch between the simulated (also termed synthetic, predicted, replica, modeled) and measured pressure fields, the model is rerun with a new set of bottom parameters. After many searches, usually involving optimization techniques, a best fit may be found. The correponding bottom parameters can be viewed as candidates for true ones.

The use of advanced mathematical models for geoacoustic inversion has been practiced for more than a decade.

3.2 The acoustic wave equation

The basic physical model of sound transmission in a fluid like air or water is the acoustic wave equation

$$\frac{\partial^2 p}{\partial t^2} + \alpha \frac{\partial p}{\partial t} = c^2 \rho \nabla (\frac{1}{\rho} \nabla p) + f, \tag{1}$$

where

$p =$ $p(\mathbf{x}, t)$, acoustic pressure $[Pa]$,

$\alpha =$ $\alpha(\mathbf{x})$, rate of absorption $[1/s]$,

$c =$ $c(\mathbf{x})$, speed of sound $[m/s]$,

$\rho =$ $\rho(\mathbf{x})$, density $[kg/m^3]$,

$f =$ $f(\mathbf{x}, t)$, acoustic sources $[Pa/s^2]$,

$\mathbf{x} =$ (x, y, z), cartesian coordinates, $[m]$,

$t =$ time, $[s]$.

There are three environmental parameters in the physical model (1), the speed of sound, the density and the absorption rate. For seawater the density and absorption are known, while the speed of sound is measured by CTD or XBT profiling. When a sound wave hits the bottom, the wave is partially reflected and partially transmitted into the bottom. The acoustic properties of a soft sediment is similar to a fluid. In order to apply the wave equation in the sediment, its speed of sound, density and absorption need to be known. Consolidated sediments, or bedrock, possess substantial rigidity. Then there are two additional bottom parameters, namely shear velocity and shear absorption rate. In addition the wave equation is replaced by a system of elastic wave equations. Next in ascending order of complexity is Biot theory in which the sediment is considered to be a multiphase medium with an elastic frame filled with pore water and gases. The most important Biot parameter, besides those mentioned, is the flow permeability. The actual description of bottom data being used is termed the geoacoustic model.

The wave equation, or its extensions, with a specified source and environmental parameters constitute the forward model. The significance of the forward model is that the pressure at any field observation point can be found by numerical solution of the forward model.

3.3 Trade-off between model resolution and computational speed

The processing time (CPU time) for the solution of the propagation model is always a main concern, despite the rapid growth of computer power. If the geoacoustic model is too complex, the CPU time may become unreasonbly large. There is a large variety of numerical methods which takes advantage of simplifying features of the environmental description. A common way to simplify the media input is to assume that all parameters depend only on the depth-coordinate (range-independence). It also means that the bathymetry is flat. Such a model may be acceptable if it is applied within just a small area. Solutions to wave propagation problems with range-independent data can be found within a second. Weakly range-dependent models require much more CPU time. Cost-effective numerical methods for full 3-D variations is presently under development.

Finding a good balance between model accuracy and computational cost may be decisive for the success of an inversion scheme. Generally speaking, the resolution of the geoacoustic model should be adequate for the current purpose. An overly specified description may exhaust human as well as computational resources without justification. The single most important factor is the frequency range of the acoustic source, often related to the water depth. The spatial resolution needed of media parameters diminishes at lower frequencies. On the other hand, low-frequency sound penetrates to larger depths, and it is more affected by shear wave conversion and attenuation. The frequency contents of the probing signal is part of the experimental setup. The experiment must be configured with great care so that the desired goal may be achieved. To that end, trial computations with the forward model are helpful.

For a mono-frequent signal the time-dependence of the wave field is reduced to the determination of the amplitude and phase at the sensor. Computationally pulse propagation is often accomplished by Fourier synthesis of some hundred frequencies of the spectrum of the emitted pulse. It implies that a frequency domain code is applied for the wave propagation problem for each frequency being used in the approximation of the continuous spectrum. In contrast matched field inversion in the frequency domain is commonly done with a few selected frequencies. The benefits of transient sounding must be weighed against the increased computational burden of using a large number of frequencies.

Next two experiments, which can be considered as representative for matched-field inversion in the time-domain, are briefly reviewed.

3.4 The YELLOW SHARK experiment

This experiment was conducted by SACLANT Undersea Research Center, La Spezia, Italy, in a shallow water area south of the island Elba, off the west coast of Italy, in September 1994 [21]. A static configuration was applied along a 15 km mildly range-dependent track. The water depth varied in the range 111-116 m. The sound speed profile of the water was downward refracting with a sharp transition at a well-developed thermocline at the depth 20 m. The receiver, a 63 m vertical line array with 32 hydrophones, was moored at one end of the track. The transmitter was deployed at middepth at four distances, 4.5, 6, 9 and 15 km, from the array. The emitted signal from a flextensional projector was a 200-800 Hz LFM with a pulse duration of 12 s. The fitness function was formulated as the gain of a model based matched filter including both time and space coherence. Inversions based on a single, as well as combinations of hydrophones, were studied. A reference geoacoustic model was set up using knowledge from archival sediment data bases supplemented by reflection profiling along the track. The inversion model was defined as a sediment layer and a half-space. The search space comprised the velocities and attenuations of both layers, and the velocity gradient and thickness of the top layer. Both range-independent and range-dependent wave propagation modeling were tried using normal- and coupled modes. The optimization algorithm was based on sequential quadratic programming with line searches. Inversions were done separately for data from the four distances, resulting in average geoacoustic estimates over these distances. For the 9 km separation the velocities of the two-layer inversion model were estimated to 1437 and 1532 m/s and the attenuation to 0.05 and 0.13 dB/λ. The thickness of the top sediment was found to be 9 m with a velocity gradient equal to 2.4 s^{-1}. The agreement between measured and predicted pressure values based on the optimal parameters was excellent. Inversion results based on a single hydrohone (near bottom) or combinations of hydrophones were about the same. Each inversion was completed by a few hundred of modeling runs.

On the grounds that data lacked sufficient information on density, this parameter was excluded from the inversion. The ambiguity of the estimated attenuation coefficients was large.

The static configuration being used is not essential. A similar inversion experiment with drifting acoustic buoys was successful.

3.5 The MAPEX2000 experiment

This experiment was conducted by SACLANT Undersea Research Center on the Malta Plateau in March 2000 [22]. The water depth along the 9 km track varied in the range 100-130 m. The sound speed was around 1500 m/s with very small variations both in range and depth. A towed horizontal array with 128 receivers was used. Only two hydrophones with the offsets 300 and 428 m were used for the inversion. Utilizing data from just one hydrophone degraded the results, while the improvement of using more than two was insignificant. The source was mounted in a fish and towed with the receiving array at midwater depth. Two chirp signals were emitted in the bands 200-800 Hz and 800-1700 Hz with the pulse length 1 s. The track was divided into segments with the length 1 km. Range-independent inversion were applied for each segment. After matched filtering the fitness function was defined as the correlation coefficient between the envelopes of the measured and simulated time-series. The latter was generated by a ray based propagation model. The geoacoustic model of each segment consisted of a two-sediment layer bottom and an infinite half-space basement encompassing six parameters. The attenuations of all layers were kept fixed in the inversion because data provided insufficient information. For the same reason the density was set to be the same in all layers. The inversion results agreed well with previous inversions along the same track using frequency sounding.

3.6 Comparisons between the YELLOW SHARK, MAPEX2000 and v35 experiments

Curiously enough, in all cases the thickness of the top sediment was around 10 m and its velocity was somewhat less than the sound speed of the water at the bottom.

The main difference between the two experiments in the Mediterranean Sea was the use of a moored vertical array and a towed horizontal array respectively. If a towed source is used with a stationary vertical array, large areas can be covered, and extended propagation distances would probably increase the information content of the bottom in received signals. However, as the range increases the variability of the environment may necessitate a range-dependent inversion, which would incur a larger computational cost. The advantage of a towed horizontal array is that it can be deployed and operated from the towing ship. Because of the short distance between the source and the receiving array a range-independent inversion may be applicable, offering the prospect of performing inversion in real time.

Both YELLOW SHARK and MAPEX2000 failed to determine densities, and the confidence of absorption estimates was poor. In contrast, all geoacoustic parameters were well determined in v35 because all inversion results were based on signals that travelled in the sediments alone. The rich information content of the targeted parameters was made possible with bottom-located transmitter and sensors. Such a static configuration is applicable only in limited areas of exceptional importance, or as a substitute of corings for ground truthing.

The observation made in MAPEX2000 that the use of two well separated hydrophones, instead of a single one, markedly improved the estimates of both the velocity and thickness of the top sediment, is explained by the fact that information on arrival times at two hydrophones is enough to resolve the velocity-depth ambiguity. Further resolution power in MAPEX2000 would have been gained by towing at a larger depth.

The inversion results in v35 were obtained in a hand-made fashion by comparing arrival times and amplitudes of echoes of data, and those from a ray based model. This process needs to be automated as in the other two experiments using matched field concepts. Usually matched field inversions require thousands of forward calculations. In the YELLOW SHARK experiment merely a few hundreds were enough, probably due to a clever formulation of the fitness function.

4 Conclusions

4.1 A long-term database strategy

Learning classification of sediments by visual examination of seismic traces is a training process involving comparisons with other evidence such as core samples. Besides much human labor, this technique lacks precision. For example, even though a layer is recognized as sand, its velocity may vary in the range 1600-1850 m/s depending on grain size. However, the grain size cannot be discerned from the trace plot alone.

The new trend is to use physical models to reproduce the individual traces. The model predictions are driven by geoacoustic parameters, which are varied until a good fit with measured responses are found. Once these parameters have been estimated, a classification in terms of till, sand, silt etc may be done by using the same correlation tables as before but in reversed order. Therefore inversion by physical modeling is equally important to both the geological and naval research communities. It also means that the creation of a database of geoacoustic parameters is a mutual interest.

Physically based inversion techniques are in their infancy, and no one can foresee when, or if ever, they will supersede the conventional ones. The difficulties in remote technology are respectable, and a combination may turn out to be the best approach.

Nevertheless a description of marine sediments in terms of geoacoustic parameters makes sense, simply because the importance of acoustic techniques are increasing. For example, the present maps of grain size distributions are difficult to validate as opposed to a database of geoacoustic parameters. The latter is validated in the same way as it was produced, namely by performing wave propagation experiments in which the acoustic response of the seabed is measured and compared with those predicted by simulation models driven by the parameters of the database.

4.2 A capable tool for sediment mapping

The center frequency of a sub-bottom profiler is usually a few kHz, which is somewhat too large for measuring geoacoustic properties of interest for low frequency sound. Another drawback is the weak ability to determine how the velocity depends on the depth coordinate. Nevertheless, the output in the form of a reflection profile provides a structural overview, from which an average velocity and sediment thickness may be inferred. Sub-bottom profiling is helpful in both the design, and cross-checking of results, of more sophisticated approaches. The claim made by suppliers that sub-bottom profilers offer automatic sediment classification by trace analysis must be examined carefully, since a number of restrictions apply. Anyway, merely the use of a chirp signal source improves the possibilty to apply model analysis of the traces.

4.3 Geoelectric sounding of sediments

Our knowledge of marine geology is the result of integrating information from echo sounding, gravity and magnetic sensors, seafloor coring, bottom photography etc. No single method would suffice. In sediment mapping there are several similarities between acoustic and electric soundings, which could be exploited to mutual benefit.

Geoelectric sounding in the ELF and VLF bands for electric conductivity has been the target of several inversion studies in marine electromagnetics [6],[7],[8]. These investigations indicate that the depth to the bedrock interface can be determined in an affirmative way. One reason for this is the huge conductivity contrast seawater/bedrock (around 1000).

Another advantage is that diffusive electromagnetic waves suffer little from scattering by cobbles and gravel lags. This is attainable in the acoustic case only by low-frequency signals, which are difficult to generate by a controlled source of sufficient power output.

The electric conductivity or its reciprocal, the resistivity, is a parameter which is sensitive to saline fluids in pores or fractures. An empirical relation between the bulk resistivity and porosity (volume fraction of pores) is given by Archie's law [23]. There are also correlations between the porosity and the geoacoustic parameters [24]. Therefore conductivity measurements should allow conclusions about the acoustic properties.

4.4 In the best of all worlds

Figure 3 envisages an electro-acoustic probing system in real time, which is a blend of the merits of all methods presented.

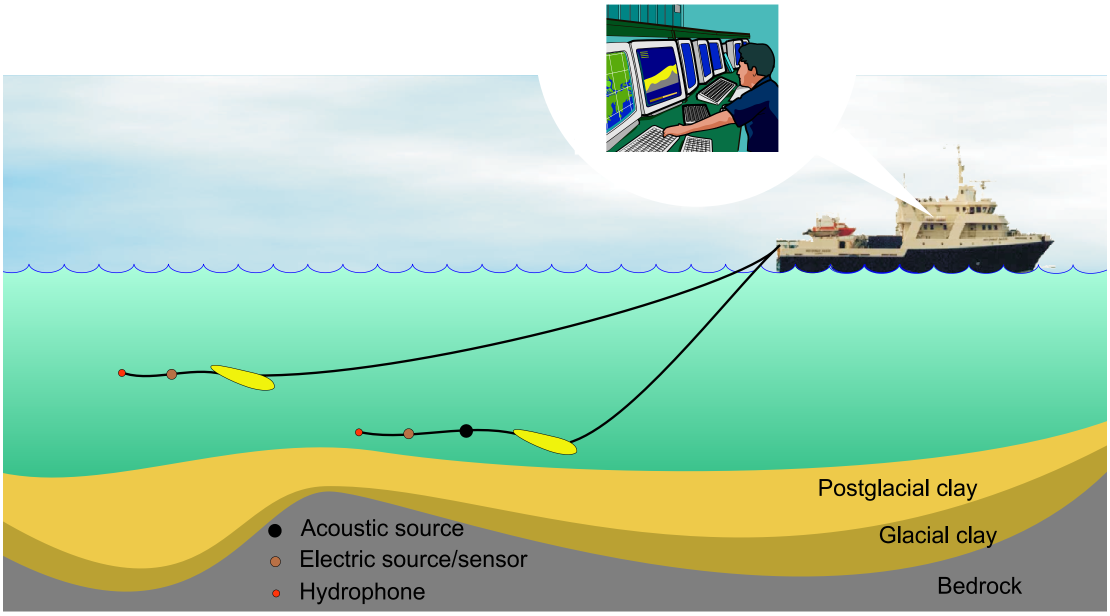

Figure 3: *A vision of an electro-acoustic probing system for sediment mapping in real time.*

The key components of such a system are:

- towfish technology and multibeam hydrographic presurveying are utilized for safe navigation close to the bottom
- the distance between the fishes, and the spectral content of electro-acoustic pulses, are automatically tuned to sub-bottom variations for optimal resolution
- matched-field inversion in real time based on ray models in acoustics
- occupation of a sizeable research vessel

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In the course of this work my perception of marine geology was greatly enhanced thanks to Per Söderberg and his unique collection of rolls of field data, a sample of which is shown in Figure 1.

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