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ASSESSING THE BOTTOM-INTERACTING SONAR ENVIRONMENT

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Assessing the Bottom-interacting Sonar Environment

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1. Introduction

Many ocean acoustics laboratories—including DREA—have contributed to a large body of research that has explored the physics of bottom-interacting ocean acoustics, identifying the physical processes governing the propagation of sound in the ocean and its offshoots: ambient noise and reverberation. What remains to be done is to isolate the geo-acoustic parameters that really matter in a given scenario and to develop reliable techniques to measure them in unsurveyed areas. This requires not only a deep appreciation of the physics (theory), but also of what is technically feasible (practice). Models and modelling are a key element of Rapid Environmental Assessment (REA): they are an integral part of any inversion process. Environmental properties obtained through the application of scientific models can be used in operational sonar performance prediction models, and reverberation model-data differences can be used to map anomalous scattering features on the seabed.

Naval sonars operate in a variety of oceanographic and geophysical environments, and predicting or simulating sonar performance for both active and passive sonars continues to be an art based on scientific principles. Apart from the expected characteristics of sonar target and the specification of the sonar array, the sonar modeller needs to know much about the acoustic environment that conveys the desired signal and—at the same time—introduces noise and/or reverberation that clutter the display. We regard models as an essential component of any sonar system, but they must be used with care; the results of the most physically-correct and computationally-accurate ocean acoustic propagation models can be no more reliable than the inputs provided. As it may be unrealistic to expect that environmental databases will exist for all possible naval theatres, an alternative solution is to attempt to survey the operational area just prior to deployment, in attempt to quickly assess the sonar operating environment. As time will be precious, the goal of such a rapid environmental assessment (REA) would be to determine those features of the environment most important to the sonar modelling task, rather than to paint a comprehensive oceanographic and geophysical portrait of the area. This paper will review the highlights of DREA's foray into assessment of the seabed properties, including: matched-field inversion for geo-acoustic properties, seismo-acoustic inversion for shear wave properties, a temporal survey of shallow water ambient noise, and use of reverberation data to extract bottom loss and seabed scattering properties. Although oceanographic aspects will be touched upon, the emphasis will be on assessing the geo-acoustic environment presented by the ocean bottom and the layers of the seabed beneath.

2. The sonar oceanographic environment

The basic sonar problem is the detection of a signal masked by the presence of noise and/or reverberation. A passive sonar detects a target by sensing its self-generated sounds: the received signal depends on the source strength and the transmission loss; the masking noise is the ambient noise background. An active sonar "pings" on the target, the received echo level depends on the active source level, the two-way transmission loss, and the backscatter strength of the target; the masking ambient noise is augmented by the reverberant energy of the outgoing ping scattered back to the receiver by the environment.

The transmission loss, ambient noise, and reverberation can be considered as environmental quantities, and can be measured. Alternatively, they can be predicted, if more fundamental environmental quantities are known. Figure 1 illustrates the relationships between environmental, acoustic, and sonar models. Models for predicting transmission loss are relatively mature. Further models (usually built on propagation models) have been developed for ambient noise and reverberation, but they require many transmission loss predictions from all directions. In addition, ambient noise models need information about the noise sources (such as ships, weather, and marine life); and reverberation models need information about scattering features (surface, volume, bottom, and sub-bottom).

Signal processing issues are important for sonar prediction models. A number of issues—such as noise and signal fluctuations, time spreading and frequency

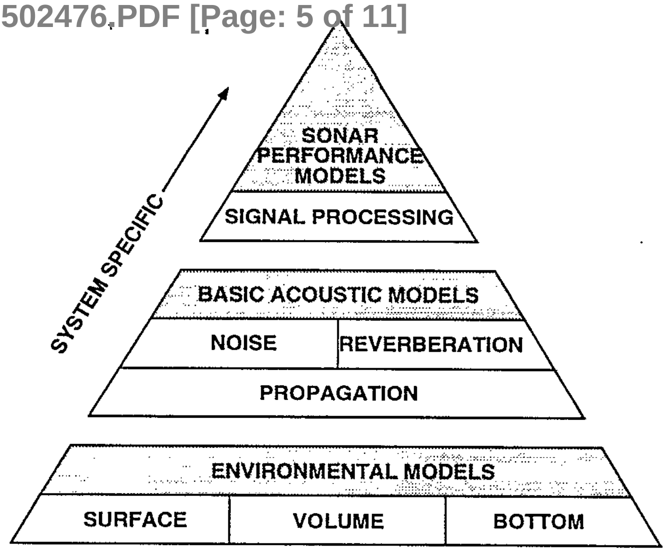

Figure 1. *The pyramid showing the relationship between the environment and models, after Etter [1].*

spreading—are related to the environment, but are research topics and beyond the current scope of DREA's REA activity.

Environmental properties of the ocean surface and water volume are reasonably accessible through remote sensing or direct measurement; seabed information is much harder to obtain, and often only available by acoustic means. Seabed properties are particularly important for shallow water, since acoustic propagation in much of the world's shallow ocean waters is dominated by bottom interaction. Also, seabed properties are more durable, in the sense that they do not need to be repeatedly re-surveyed, once measured. In this paper we concentrate on the assessment of seabed geo-acoustic properties important for ship sonar frequencies. (Although the bottom is even more important for mine countermeasures, we do not include MCM activities in our considerations.)

2.1 Sound speed

The most important oceanographic factor affecting sonar performance is the sound speed profile. Generally, the ocean is stratified, i.e. variations in depth are much more pronounced than lateral variations. The sound speed profile guides the transmission of acoustic energy from source to receiver, and controls whether the sound travels unimpeded, is refracted upwards towards the surface or downwards towards the bottom, or is even ducted by a sound speed minimum. It is essential to have a representative sound speed profile for the operational area—even if it is a single snapshot—and this is readily obtainable from ship-deployed or air-deployed expendable bathythermographs (XBTs). Multiple casts over an area would improve the assessment of prevailing conditions and may provide information on geographical variations that might interfere with sonar operations, such as ocean fronts, eddies, and currents.

To model such complications intensifies the task enormously. If the environment is geographically invariant (i.e. range-independent), acoustic propagation is cylindrically symmetrical, in effect reducing the computational problem to two dimensions. Lateral variation of the ocean water mass requires three-dimensional modelling capability, or serviceable approximations to this. As the complexity of the environment and modelling task grows, so does the susceptibility to error.

2.2 The role of ocean circulation models and remote sensing

Validated ocean circulation models—supplied with up-to-date temperature, current, and salinity profiles in an area of interest—may provide a forecast good for several days, but may only be useful in alerting the operators to sonar-unfriendly ocean features rather than providing precise inputs to sonar models [2]. In the same vein, remote sensing of ocean surface temperature may provide important background information, but it is not clear that these data can be mapped into sound speed profiles useful for sonar modelling.

2.3 Ocean surface roughness

An agitated ocean surface introduces loss (by scattering) for energy reflecting from the sea surface and creates reverberation through backscatter to the sonar (for an active sonar). The geometrical roughening of the surface is the principal physical factor leading to these phenomena, but clouds of micro-bubbles just beneath the surface may also contribute. Reflection loss and surface backscatter coefficients are typically correlated with ocean waveheight, "sea state" or local wind speed, estimates of which are readily available on-site or from remote sensors.

2.4 Acoustic ambient noise

As passive sonar detection is a signal-in-noise problem, estimating the ambient noise levels (for a single omnidirectional hydrophone) and the horizontal and vertical directionality (for hydrophone arrays or directional sensors) is just as important to the sonar prediction model as simulating the signal level. Statistical ambient noise data exist, but the coverage is spotty both in geography and season. A particular problem is the influence of nearby shipping, which generates extra noise that is highly variable in time and direction. The changeable and unpredictable nature of ambient noise seems to dictate that an *in situ* measurement at the time would be the best estimate (if the sonar has provision for scientific data collection and reduction). Alternatively, one might consider signal processing techniques such as adaptive beamforming, whereby the signal processing algorithm attempts to account for the changing noise environment.

2.5 Ambient noise modelling

Models exist for simulating noise fields, but these are essentially variants of ocean acoustic propagation models. Assuming a distribution of sea surface sources and/or a distribution of ocean shipping, the propagation models sum up the contributions propagating from all sources to the receiver location, resulting in a simulation of the levels and directionality of the ambient noise field. Particularly in shallow water, the acoustic reflection characteristics of the seabed influence the properties of the noise field (and the signal field!). Also, three-dimensional propagation models may be required to model noise arriving from sources at any bearing or range.

2.6 Bathymetry

The depth of the ocean is another important oceanographic input, needed to account for acoustic energy reflected and scattered from the seabed. (If there is significant bottom interaction, it is the most important oceanographic input.) Echo sounders can provide depth under the vessel; multi-beam echo sounders produce swaths of bathymetric data. At a given geographical location, the ocean depth does not change significantly in time, so bathymetric databases are a reasonable source of data, provided the coverage and resolution are adequate. Even with a range-independent sound speed profile, a sloping or irregular ocean bottom introduces the need for range-dependent or three-dimensional propagation models. Water depth is crucially important in shallow water (i.e. on continental shelves), as the degree of bottom interaction is much greater for a given source-receiver range in shallow water than for the same range in deep water.

The bathymetry is a key feature in determining reverberation. Unless the sonar is very directional, bottom reverberation will dominate the reverberation field. In deep water multiple surface-bottom reflections (fathometer returns) dominate at short times, while feature scattering (e.g., basin margins and seamounts) dominates at long times; in shallow water backscattering from slopes (banks, islands or the coast) dominates. In addition to the large-scale bathymetric slopes, there is the small-scale roughness that determines the local scattering. Discussion of reverberation due to backscattering from the seabed is deferred to a later section.

3. The sonar geophysical environment

The role of the seabed as an acoustic reflector and scatterer has been mentioned. In a bottom-interacting acoustic multipath environment, the acoustic reflection and scattering properties of the seafloor influence sonar performance. Shallow water (continental shelves) could be considered an extreme multipath environment in which the acoustic influence of the seabed is paramount. There are almost as many ways to parameterize the acoustic effect of the seabed as there are computer models that claim to account for the effect.

As this is the main thrust of this paper, the parameters will be introduced first as a group, and the discussion of assessment methods will follow.

3.1 Geo-acoustic propagation parameters

Bottom-interacting ocean acoustic propagation models need several or all of the following seabed parameters as input data, either as constants, piecewise constant functions of depth, or continuous functions of depth, with lateral variations included, if appropriate:

- sound speed (pressure or compressional wave)
- density
- attenuation coefficient of compressional wave
- shear speed (transverse or rotational wave)
- attenuation coefficient of shear wave.

(Bottom or inter-layer roughness—in the context of reflection loss—is another important parameter, but many models are unable to handle it.)

Some models simply replace a detailed treatment of acoustic propagation within the seabed with a frequency-dependent and angle-dependent plane wave reflection coefficient. If the representation of the acoustic reflection process is accurate, this is all one needs, as the sonar and the target are in the water (a safe assumption). The details of the acoustical processes within the seabed are not needed, only their net effect on the sound field in the water column.

3.2 Acoustically equivalent seabeds

Enlarging on this last point, it may not be necessary to have a geophysically precise representation of the seabed at all, provided the net acoustic effect is modelled adequately for the sonar modelling task. To this end, for each real seabed, there exists a family of acoustically equivalent seabeds that produce the desired effect, but whose particular parameters may not match. For example, it has long been known that the contribution to near-grazing bottom loss by conversion of energy into low-speed shear waves in the seabed can be mimicked by slightly decreasing the density and slightly increasing the attenuation of the compressional wave. This technique is particularly helpful if the propagation model at the heart of the sonar simulator knows nothing about shear waves. The equivalent seabed is—in general—frequency-dependent. The concept is similar to interpolating a curve of reflection loss vs. grazing angle, as used in many ray-trace models.

3.3 Scattering and reverberation parameters

The ocean bottom scatters sound in much the same way—and has much the same effect on sonar operations—as the ocean surface, with some important differences. Firstly, the scattering properties vary slowly with time and they are fixed in geographical location, so using databases to store and retrieve scattering parameters is a feasible option. Secondly, as sound penetrates to some extent into the seabed (more so at lower frequencies), the seabed structure beneath the water/seabed interface must be considered. Theoretical backscattering models based only upon scattering from rough surfaces do not seem to tell the full story: there is evidence that fine-scale variations of acoustic properties within the volume of the seabed just beneath the surface have a large influence. If this is so, then translating geophysical data from databases into scattering parameters may be overwhelmed by the considerable amount of high-resolution data required for the task. Alternatively, the scattering and backscattering properties of the seabed could be surveyed at the frequencies of interest and stored. Again, an *in situ* measurement at the time of deployment may be the best solution, although this would dictate that scientific reduction of acoustic data be included in the sonar processing software suite.

The vast literature on scattering attests to the difficulty in treating the process mathematically. For sonar modelling purposes, an empirical approach is generally used. Frequency- and angle-dependent scattering functions derived from measurements are used for surface and bottom scattering, and used in sonar models. The wind speed or sea state is the key parameter correlated to surface scattering. Bottom scattering is highly variable, and not readily deduced from fundamental physical quantities. It is therefore an important parameter for determination through REA techniques. The use of scattering functions to describe the effect of the environment is similar in principle to the equivalent seabed concept.

4. Assessing the geo-acoustic environment for sonar

4.1 Traditional survey methods (direct measurement)

Geophysical survey techniques developed for oil and gas exploration and other seabed activities have provided data relevant to bottom-interacting ocean acoustics. High-resolution vertical-incidence seismic profilers (i.e. echo sounders enhanced to process sub-bottom reflections) provide information on layering in surficial sediments, and have lately been improved to provide approximate sediment classification. However, these devices do not directly provide sediment geo-acoustic parameters, which must be extrapolated from direct measurements on associated core samples or boreholes. Deep-towed geophysical arrays can measure the compressional speed using critical-angle seismic refraction methods. Sidescan sonar provides a qualitative measure of seabed roughness; some multi-beam echo sounders can reduce returns to give seabed backscatter coefficients.

4.2 Inversion techniques

In many cases the bottom is inaccessible to direct measurement and inversion techniques are used. The procedure involves making a measurement (such as transmission loss) then comparing to a model prediction based on some measured or assumed environmental inputs (perhaps from a database). The differences are then compared, and used to obtain improved estimates for the desired environmental inputs (such as geo-acoustic parameters). The conceptual procedure is illustrated in Figure 2.

Inversion can be done manually, whereby an expert makes some educated guesses and achieves reasonable agreement between model and data. An alternative is an inversion algorithm, where a parameter space is searched to find an optimum (or near optimum) fit to the data. This may be computationally intensive, and the physical solution may not be very realistic.

4.2.1 Repetitive forward modelling

To characterize the geo-acoustic environment more exactly, the ocean acoustician combines available information from traditional survey techniques or databases, makes an educated guess of the remaining parameters, and attempts to model measured acoustic propagation loss as a function of range at a series of frequencies, attempting to at least reproduce the trend of the data, if not the details. It is rare that the first try is even close, but this depends upon the experience of the modeller. Through a process that has come to be known as "repetitive forward modelling", an experienced modeller can refine the parameters of the input model to achieve reasonable agreement, provided that the propagation model has accounted for all the physical processes involved in the experiment.

4.2.2 Acoustic matched field inversion

Inversion techniques start with the measured data, apply them to a model, and provide estimates of model parameters using a disciplined and reproducible method implemented on a computer. Matched field inversion uses actual measurements of the ocean acoustic pressure field generated by a known source measured at an array over a short time interval: a small space-time "snapshot" of the field. This snapshot is compared with a replica of the same

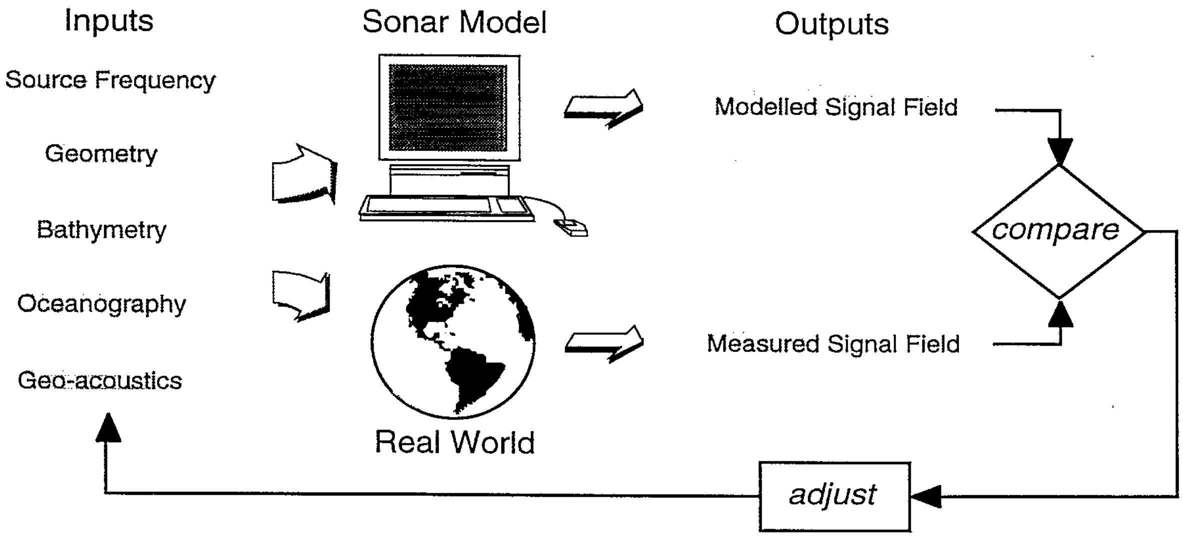

Figure 2. An illustration of the concept of matched field processing for source localization or environmental inversion.

simulated with an ocean acoustic propagation model. The mismatch between experimental and simulated fields is quantified and—through a process of automated repetitive forward modelling—the mismatch is reduced to an acceptable level, producing a set of best-estimate geo-acoustic parameters.

4.2.3 Seismo-acoustic inversion

Using sources and receivers (geophones and/or hydrophones) on the seabed tens or hundreds of metres apart, one can generate and receive interface waves at the ocean/sediment boundary whose speed of advance is strongly dependent upon the depth profile of shear speed. In areas where bottom reflection loss due to excitation of shear waves is significant, this technique is an important investigative tool. For seismo-acoustic inversion, the speed of the interface waves is determined over a wide frequency band and matched to model predictions, either by repetitive forward modelling or by automated non-linear least-squares minimization.

4.2.4 Inversion of reverberation data

Inversion of reverberation data can be used to estimate geo-acoustic and scattering parameters. Reverberation data are compared to the prediction from a shallow water reverberation model for which the sound speed profile is known, and a reasonable geo-acoustic model is available. The bottom scattering characteristics are unknown, so Lambert's rule with an assumed backscatter coefficient is adopted. The prediction usually disagrees with the data, so the backscatter strength is adjusted manually to achieve acceptable agreement with the data. The procedure is typically repeated at a number of frequencies. These estimates can then be used in models for sonar performance predictions.

The resulting scattering strengths depend on the assumed geo-acoustic model, and consequently are sensitive to errors in it. Global inversion techniques developed for matched field processing can be used to simultaneously invert for the geo-acoustic parameters and bottom scattering. Due to the random nature of the reverberation data, there is no phase information and consequently there is less information about the environment. This may be beneficial if it leads to simple robust procedures.

5. REA and related activities by DREA and associates

Defence Research Establishment Atlantic has a long history of ocean acoustics research, including bottom-interacting ocean acoustics, particularly in shallow water [3]. DREA has several active sea-going research groups collecting environmental data, using a variety of research systems deployed from the acoustically-quiet research ships CFAV QUEST and CFAV ENDEAVOUR.

(Equally significant is work that was performed at Defence Research Establishment Pacific. Work at that laboratory continues at a reduced staffing level as Esquimalt Defence Research Detachment, a new division of DREA. EDRD also has an active ongoing research thrust on mine countermeasures. Other research activity has moved to industry and the Underwater Acoustics Chair at the University of Victoria.)

The fundamental goals of DREA's Rapid Environmental Assessment activity are:

- Timely products to support sea and air operations
- Improved measurement and inversion techniques
- Better inputs and models for Canadian naval and maritime air sonar simulators
- Support for in-house development projects

At present, DREA's emphasis is to validate the scientific basis of techniques that would be included in an REA initiative, with a lower level of effort applied to creating REA products for operational use. Our investigations and model development continue to be guided by the requirements of the Canadian Navy and Air Force for sonar performance prediction.

5.1 Bottom-interacting ocean acoustics

DREA has favoured two shallow water sites on the Scotian Shelf for its shallow water acoustics experiments: one has 75 m water over a sand bank, the other has 210 m of water over a clay basin. Recent experiments have collected data for geo-acoustic inversion, matched field inversion, matched field localization, ambient noise studies, and adaptive beamforming with vertical arrays. In addition, we have sponsored a year-long ambient noise survey of 4 shallow water sites through monthly deployments of sonobuoys from aircraft. DREA collaborates with the Ocean Acoustics Chair at the University of Victoria and supervises contract work in these areas.

5.2 Matched field inversion (MFI)

This method of environmental assessment has made much progress in many directions, but is far from being a standard tool. There have been amazing successes and dismal failures, as reported at a 1996 workshop [4] at EDRD (to be repeated in 1997). Currently, DREA research is focussed on sensitivity studies to determine which seabed parameters have the most influence on the water-borne acoustic field, and hence which are most accessible through MFI. Also, DREA is participating in a challenge to invert a benchmark set of simulated matched field data of progressive difficulty, to test MFI algorithms. Through contracted research, two experimental data sets from the DREA test sites are being reduced using MFI. It is expected that MFI will eventually become an important tool for REA in support of sonar modelling, but not a panacea.

5.3 Seismo-acoustic inversion

As part of a study on the use of geophone sensors in underwater acoustics, DREA collected data on interface wave dispersion that was successfully inverted to provide shear speed profiles at the two DREA test sites. Figure 3 shows the results of interface wave dispersion experiments at sites with clay/silt bottoms [5]. In these cases, the "staircase" profile may be an approximation to a continuous power-law profile, as suggested in the figure. The experimental and data reduction methodology for this work removes it from the "rapid" category of techniques; however, researchers at the University of Victoria plan to compare these results with matched field inversion of acoustic data recorded at the same site on a vertical line array. This may be the first attempt at directly comparing results of seismo-acoustic inversion and acoustic matched field inversion.

5.4 Ambient noise studies

A year-long survey consisting of monthly snapshots of ambient noise at four shallow water sites will provide a useful database for sonar modellers. Further analysis of the results may provide insight into the relation between ambient noise levels and bottom type. A model for noise coherence at vertically-separated shallow-water sensors has shown the combined influence of the sound speed profile and the acoustic reflectivity for the sea floor on the vertical directionality of the noise field [6]. Figure 4 illustrates the influence of a downward-refracting sound speed profile on noise coherence. A survey of historical DREA ambient noise measurements has been performed and compiled in summary form.

5.5 Equivalent seabed models

Through contracted and in-house research, a search is underway for the optimal representation of the acoustical effect of the seabed in the context of sonar operation. The goal is to eliminate geo-acoustic parameters to which sonar operation is insensitive and to generate an irreducible set of robust geo-acoustic parameters. It may then be possible to devise experiments to rapidly and reliably assess these parameters in previously unsurveyed areas of interest (possibly using acoustic matched field inversion). An important complement to this work would be to develop translation algorithms that would generate the ideal parameter set from traditional geophysical databases.

5.6 Reverberation measurements and analysis

A large portion of DREA's effort is in support of integrated active and passive sonar systems. An active sonar system is under development for Canadian towed-array ships. For the patrol aircraft a processing system for sonobuoys is also being developed, with both monostatic and bistatic active sonar capability. Alongside this, a range-dependent shallow water active sonar modelling capability is being developed for DREA's research purposes and for incorporation in the Canadian version of the NATO prediction system AESS. We feel that integrated modelling capability is important for the sonar systems. The integration of AESS with the towed array development is also being investigated.

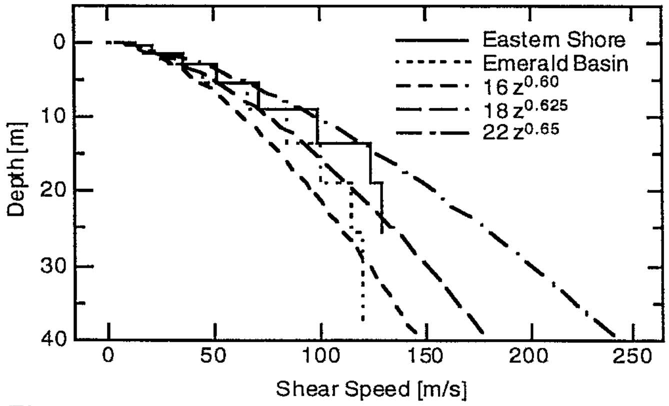

Figure 3. Seismo-acoustic inversion: shear speed profiles determined from interface wave dispersion data measured with an ocean bottom seismometer.

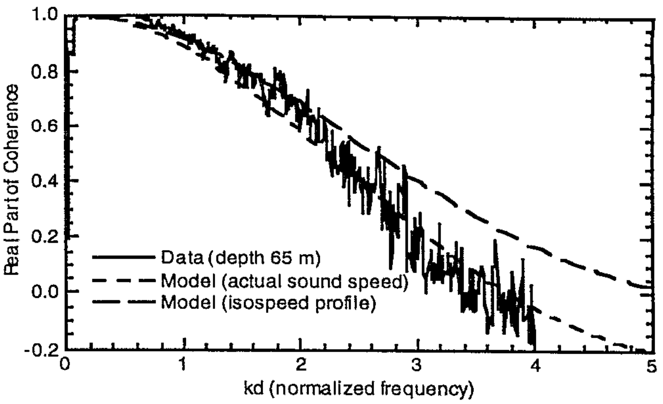

Figure 4. Ambient noise studies: noise coherence between two sensors on a vertical array in shallow water. The downward-refracting sound speed profile has a profound effect on the noise coherence.

Figure 5 illustrates the very simple inversion procedure described above in Section 4.2.4. Experimental reverberation data (solid line) are compared to the prediction from a shallow water reverberation model with an assumed backscatter coefficient of –27 dB [7]. Adjusting this coefficient to -35 dB improves the fit. Figure 6 shows backscattering strengths obtained at several frequencies at two different sites. Results from applying global inversion techniques simultaneously to geo-acoustic parameters and backscatter parameters have been reported at a recent conference [8].

Collaborative work is important in developing REA techniques. Canada participated in the recent NATO MILOC exercise Rapid Response. Reverberation data were gathered on Alliance using the SACLANTCEN towed array. Software developed at the SACLANTCEN, DREA, and Penn State University was used to extract the reverberation time series and compare with model predictions. Key products are polar plots of towed array time series, which produce "maps" of the backscattering overlaid on the bathymetry. Examples of this type of polar

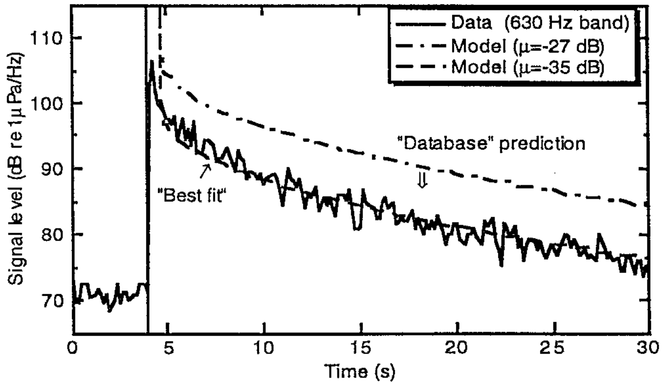

Figure 5. Inversion of reverberation: "database" and "best fit" model-data comparisons.

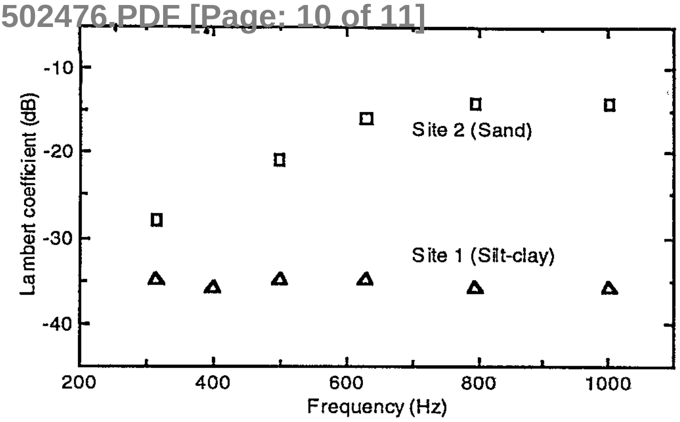

Figure 6. *Inversion of reverberation: Lambert coefficients for bottom backscattering*

plot are seen in references [9, 10]. We feel that no towed-array active sonar system should be without this feature.

In addition, estimates of bottom loss and scattering strength were obtained at several sites. This work is being supported by the (US) Office of Naval Research and further developments will be made in the 1997 exercise. The techniques will be used at DREA as well, through contracted and in-house effort.

6. Conclusions

This article has presented the DREA view on the task of assessing the ocean environment in the context of sonar operations, with an emphasis on bottom interaction effects. Many issues have been raised, yet only touched upon in a superficial way. It is hoped that the article conveys the motivation for DREA (and associated) work in Rapid Environmental Assessment, the importance we place on various aspects of the research, and an indication of where we think it will lead.

In our research, we have found that the greatest delay in model-data comparisons has been in getting the data from the measurement devices to the model for inversion.

Models are mature; databases sparse or inaccurate; inversion techniques exist; and computational power is generally available. Integration with measurement systems needs to be done, and we feel progress can be made readily. Our goal is to develop robust techniques that will be able to provide useful, and reasonably accurate, products in a timely manner.

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Appendix: A comment on the utility of databases

Despite the sophistication of the computational acoustic models which form the kernel of sonar simulators, the predictions of such systems must be tempered by the GIGO rule: Garbage In, Garbage Out. It is tempting to think that marine geophysical databases will provide a basis for constructing geo-acoustic representations of the seabed for sonar modelling, but there are pitfalls on this path. Firstly, the relevant geophysical parameters must be understood and reliably measured. Secondly, these data must be inserted into the database and available! Thirdly, one has to have well-validated scientific models for translating the geophysical characteristics of the seabed into reasonable estimates of the acoustic effects. It is our experience that databases of marine geophysical data—however helpful they are to their designers—often lack parameters crucial to the sonar modeller. For example, a database containing the geographical extent, thickness, and classification of surficial sediments is of little use without the associated densities, sound speeds, and acoustic attenuation parameters. There is also a tendency for operators to trust data in databases without questioning the pedigree: where did the data originate? how did it get here? is it validated? how much of it has been invented or guessed? We must be wary of being fooled that we have solved our problems simply because we have technology that provides ready access to vast amounts of data.

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