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SHALLOW WATER ACOUSTICS: A REVIEW OF *DREA* RESEARCH

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ABSTRACT

From 1949 to 1989, DREA conducted research in shallow water environmental acoustics in support of passive sonar applications in submarine detection. The emphasis was on collecting ambient noise and transmission loss data in a variety of geographical areas of interest with different seabed types in all seasons of the year. Significant progress was made in understanding the physical mechanisms governing the acoustic environment, especially the role of the seabed. Our modelling capability improved substantially, drawing on computer codes developed in-house and elsewhere. An important lesson learned was that passive detection is governed by the sum of transmission loss and ambient noise level, which varies from site to site much less than each component considered separately. Despite the progress made, much remains to be done, particularly with regard to the performance of hydrophone arrays in shallow water environments. The way ahead should include: experimental studies of array performance; environmental acoustics measurements relevant to active sonar in shallow water; bottom-mounted sensors (including geophones); and integration of oceanographic and geophysical databases with sonar models in three-dimensional environments.

SOMMAIRE

De 1949 à 1989, le CRDA a effectué des recherches en acoustique du milieu en eau peu profonde en vue de l'utilisation de sonars passifs pour la détection sous-marine. Ces recherches portaient surtout sur la cueillette de données sur les bruits ambiants et les pertes de transmission dans diverses zones d'intérêt géographique à fonds océanique différents en toutes saisons. Des progrès importants ont été faits sur la compréhension des mécanismes physiques qui régissent le milieu acoustique et plus particulièrement sur le rôle que joue le fond océanique. Nos capacités de modélisation se sont beaucoup améliorées grâce à l'utilisation de codes machine mis au point au Centre et ailleurs. Un point important qui a été relevée est que la détection passif est régie par la somme des pertes de transmission et des niveaux de bruit ambiant, qui varie beaucoup moins d'un lieu à un autre que chaque facteur pris séparément. Malgré les progrès qui ont été fait, il y a beaucoup à faire et plus particulièrement en ce qui a trait au rendement des réseaux d'hydrophones en eau peu profonde. Les travaux à venir devraient comprendre la mise en oeuvre d'études expérimentales sur le rendement les réseaux, la prise de mesures en acoustique du milieu en rapport avec les sonars actifs en eau peu profonde, la mise en place de capteurs au fond de la mer (y compris des géophones) et l'intégration de données océanographiques et géophysiques aux modèles de sonars dans des cadres tridimensionnels.

1. INTRODUCTION

For acousticians to predict how well their systems will work in practice, the acoustic properties of the medium—in this case the ocean—must be measured. An important type of measurement is transmission loss: how much is the sound pressure level reduced in propagating from the source to the receiver? Another is ambient noise level: what is the spectral density of the naturally-occurring noise in the ocean that provides a background against which the desired signal must be discriminated? (In this paper, we will be presenting results applicable to passive sonars, which listen for the characteristic sounds radiated by a submarine. We will not discuss the operation of active sonars, which transmit pulses of sound and then listen for echoes from the submarine.) The measurement, interpretation, and modelling of transmission loss and ambient noise are a major part of what is called *environmental acoustics* by the sonar community. Regardless of the application, the study of environmental acoustics in the ocean presents the research scientist with many challenging puzzles in a difficult setting. The ocean is a far cry from the laboratory bench!

The purpose of this paper is to provide an overview of DREA research in shallow water environmental acoustics from 1949 until 1989, spanning an interval of 40 years, but concentrating on the last decade or so. In addition, we will present what we view to be the way ahead for follow-on research. First we describe the geographical areas where much of our work has been done. Then we briefly review the key DREA publications on shallow water acoustics. We summarize the principal lessons learned in areas of transmission loss measurements, transmission loss modelling, and ambient noise. We show the importance of not viewing transmission loss and ambient noise separately, but in combination, in the form of Detection Level. Following these, we present a list of deficiencies and suggest topics that need to be studied in the near future.

Although we present actual measurements at two different sites of interest, their precise location is not important. Rather, we emphasize the relation between the measured acoustical conditions and the surrounding oceanographic and geological environment.

The shallow water areas on the east coast of Canada are shown in Figure 1. Although the breadth of the eastern Canadian continental shelf is only a few hundred miles, it is quite long: about one-quarter of the distance along the great circle route From Halifax to the UK is over the Canadian continental shelf. We also regard Canadian Arctic waters to be "shallow", but the unique acoustic environment presented by the Arctic warrants special attention, and this is one area of responsibility of the Defence Research Establishment Pacific, DREA's counterpart on the west coast.

2. BRIEF REVIEW OF KEY DREA PUBLICATIONS

It is difficult to comprehensively review 40 years of research in a brief article, but it is possible to highlight a few milestones of the work that are available in standard sources.

Early work at the Naval Research Establishment—as DREA was known then—concentrated on acoustic propagation [Sandoz **1949**, Longard **1952**, MacPherson and Fothergill **1962**] and noise [Piggott **1964**] applied to the sonars and sonobuoys of the time, which generally operated above 100 Hz. This early work recognized the importance of bottom loss and the role of the sound speed profile in directing energy towards or away from lossy boundaries.

A programme of propagation loss and ambient noise measurements was conducted throughout the 70's in areas of interest to Canada, using improved hydrophone arrays [Ross and Adlington **1976**, Ross 1978]. Serious modelling of experimental transmission loss data commenced in 1978 with an international experiment on the Scotian Shelf [Ellis

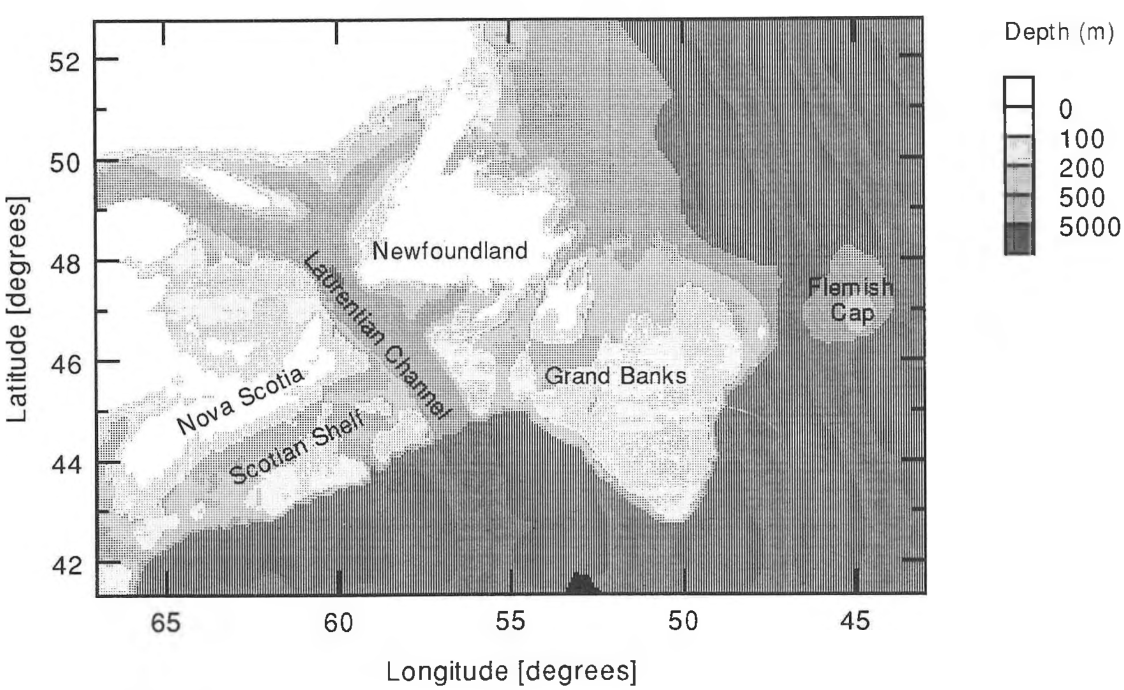

Figure 1. Shallow-water areas on the east coast of Canada.

and Chapman **1980**, Chapman and Ellis **1983**]; we found that adiabatic normal mode computer codes based on detailed geo-physical models of the seabed adequately explained observations, except perhaps in the frequency range 25–100 Hz.

Another international experiment conducted in 1981 on the UK Continental Shelf drew our attention to what seemed to be unusually large transmission losses below 300 Hz in an area of thinly-sedimented bedrock. The experimental data at this site did not submit to our normal-mode modelling attempts [Chapman and Ellis **1983**]. Motivated by suggestions of other workers regarding the role of shear waves in the seabed, a simple model incorporating shear wave effects was developed [Ellis and Chapman **1985**] to explain the phenomenon.

This investigation of shear wave effects at very low frequencies was advanced significantly by the development of improved technology to monitor propagation down to 2 Hz [Staal **1987**].

New areas were found in ice-free arctic waters and rocky coastal areas that exhibited similar high transmission loss at very low frequencies, and an explanation was found in terms of the physical mechanisms taking place within a thin low-shear-speed sediment layer over a hard bedrock substrate [Hughes *et al.* **1990**].

While we were concentrating our research on the physical mechanisms governing propagation, we also gathered and analyzed ambient noise data at several sites [Zakarauskas *et al.* **1990**].

3. CURRENT KNOWLEDGE

3.1. Transmission Loss Measurements

In shallow water, transmission loss is highly variable with respect to location, primarily due to variation in seabed type. In a typical propagation scenario, the acoustic energy reflects from the seabed so frequently that even a small change in bottom loss from site to site can lead to large differences in transmission loss at long range.

The variability of propagation is illustrated well in Figure 2, which shows transmission loss from sources at 60 m depth to receivers on the seabed 30 km away, at two different shallow water sites: Site 1 and Site 2. The seabed at Site 1 is composed of thick (10–20 m) smooth sand layers; in contrast, the seabed at Site 2 is composed of rough granite overlain by a few metres of silt. These two sites represent extreme environments: Site 1 has a low-loss seabed and

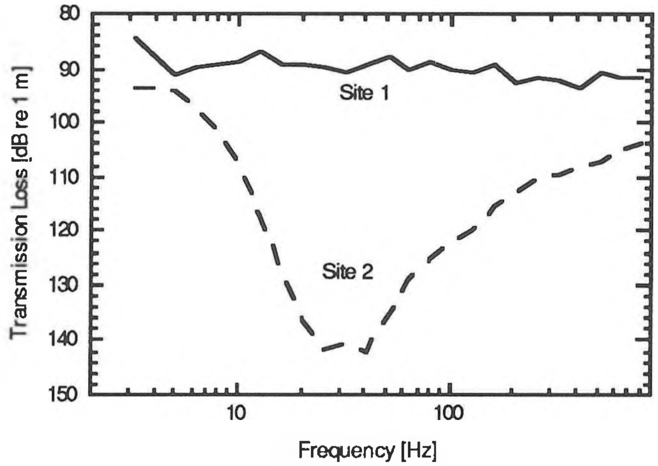

Fig. 2 Transmission loss at two shallow water sites.

exhibits good propagation at all frequencies shown; Site 2 (analyzed in detail by Hughes *et al.* **1990**) has a high-loss seabed, especially in the 10–100 Hz band, and shows correspondingly poor propagation in that band. Note that the difference in transmission loss between these two sites is 50 dB at 30 Hz!

Figure 2 represents only a very small fraction of the transmission loss data that we have collected. Reviewing all the experiments, and considering what we know of the geophysical and oceanographic environments, our principal conclusions regarding transmission loss measurements are:

- Acoustic propagation in shallow water is highly variable in time and in location.
- The geophysical composition of the seabed is perhaps the most important factor governing shallow water acoustic propagation.
- The sound speed profile (upward-refracting, downward-refracting, etc.) plays a large role in influencing to what extent the acoustic field interacts with the seabed.
- The speed of shear waves in the seabed and the thickness of the sediment layer are key geo-acoustic parameters.
- Quiet, low-noise sensors are essential. (This may require deployment on the seabed.)

3.2. Transmission Loss Modelling

We use models in two ways: (1) to interpret measured data, investigating various physical mechanisms that govern acoustic propagation and their relative importance; and (2) to predict acoustic propagation in areas and in seasons for which we have no measured data. No one model seems to provide all that we would like in an ideal model. Our general conclusions regarding acoustic modelling in shallow water are:

- Ray-based models have limited use in shallow water environments.
- Normal-mode models (such as SNAP, KRAKEN, PROLOS, described by Etter **1991**) have proven to be a useful representation of the acoustic field and have the potential for modelling range-dependent environments to some extent.
- For many seabed environments, one needs knowledge of the speeds and attenuations of the shear wave in addition to those of the compressional wave; the layering of the seabed is often important.
- Fast-field models (such as SAFARI) easily handle multi-layer seabeds with shear, but typically are restricted to range-independent environments.
- Not surprisingly, the agreement between model results and experimental measurements depends largely upon the accuracy of the input geo-acoustic parameters.

3.3. Ambient Noise

Ambient noise is the acoustic field that is generated by propagation from diverse (and often unknown) sources spread over a wide area. Accordingly, one should expect that ambient noise levels are highly correlated with transmission loss, and they are. If the propagation conditions at all the sources are the same as those at the receiver, areas exhibiting high transmission loss have low ambient noise levels, and vice versa.

To illustrate this point, Figure 3 shows average ambient noise spectrum levels from the same sites as Figure 2. The low-loss seabed of Site 1 leads to high noise levels in a broad band centred on 60 Hz; the source of this noise is usually attributed to ships. The high-loss seabed of the Site 2—and to some degree the lower shipping density—results in a very quiet environment. The average wind speed at Site 1 was 15 knots while the data were collected; at Site 2 it was only 9 knots. However, correlation analysis showed that the levels at Site 1 were uncorrelated with wind speed above 20 Hz, whereas the Site 2 levels were highly correlated with wind speed. Below 7 Hz, the noise levels are nearly identical, and may be generated by seismic activity or ocean wave phenomena. Note that the maximum difference in the ambient noise levels at these two sites is about 35 dB, near 50 Hz.

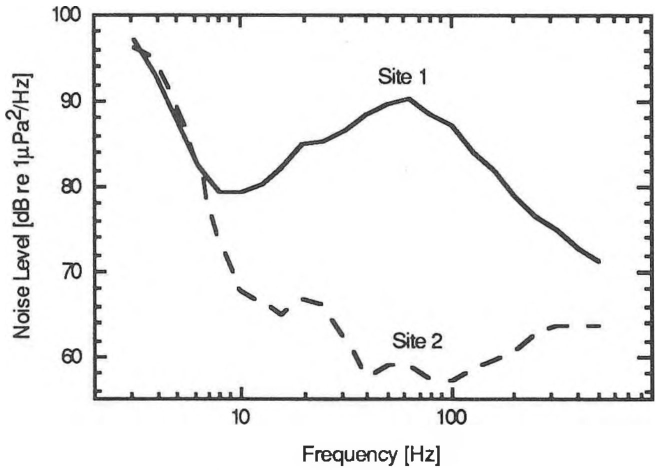

Fig. 3. Ambient noise spectrum levels at the seabed.

Our ambient noise measurements have led us to the following conclusions:

- Like transmission loss, ambient noise in shallow water is highly variable and dependent upon seabed type.
- A perpetual component of ambient noise is wind- and wave-related. Depending upon the propagation conditions, ship noise can add to this component to various degrees.
- DREA emphasis has been on measuring noise levels and statistics, rather than developing and using models.
- Simple models have shown that both the level and the vertical directionality of ambient noise are influenced by the reflection coefficient at the seabed.

3.4. Detection Level

If one is attempting to detect a submarine with passive acoustics, it is neither transmission loss alone nor ambient noise alone that governs the performance of the sonar, but a combination of the two. Mathematically speaking, if the submarine has a narrow-band source level SL and if the environment introduces the transmission loss TL and presents a background noise level N, then the signal-to-noise level at a single omni-directional sensor is

$$SNR = SL - (TL + N). \quad [1]$$

From this expression, clearly what is important in passive detection is the *sum* of transmission loss and noise level.

The characteristics of the sonar processor are summarized by its Detection Threshold (DT), which is the signal-to-noise ratio required at the input of the processor to achieve the desired detection performance (usually 50% probability of detection at a fixed false-alarm rate). The precise value of DT depends upon the statistics of the noise and the signal and generally is frequency-dependent. If we *assume* a DT value, then we can turn Eq.[1] around and ask "What source level is required for detection in a given environment at a specified range?" The Detection Level is defined to be that value of SL that equates SNR to DT, that is

$$DL = DT + (TL + N). \quad [2]$$

In other words, if the Source Level exceeds DL in a given scenario, there is a better than 50% chance of detecting the submarine. Again, notice that the sum TL+N appears in Eq.[2]. Using measured values of TL and N and an assumed value for DT, one can calculate DL values and compare them with the frequencies and levels of narrowband lines expected from various submarines.

Using the environmental data from the two sites shown in Figures 2 and 3, we present in Figure 4 values of Detection Level at a source-receiver range of 30 km, assuming a hypothetical Detection Threshold of 0 dB. In plain language, the hypothetical sonar signal processor is capable of detecting the signal 50% of the time if the signal power and noise power in a 1-Hz band are equal. (This value does not represent any particular detection scenario, but is used simply as an example.) Although there are significant differences in computed Detection Level between the two sites, the differences are not as large as one might expect from looking at transmission loss and ambient noise separately. Whereas the maximum difference in transmission loss is 50 dB and the maximum difference in noise level is 35 dB, the maximum difference in detection level is only 30 dB. Also, there are significant frequency spans in which the difference in detection level is less than 10 dB or even less than 5 dB.

The frequency of minimum Detection Level does not always coincide with the frequency of minimum Noise Level or the frequency of minimum Transmission Loss. That is, the

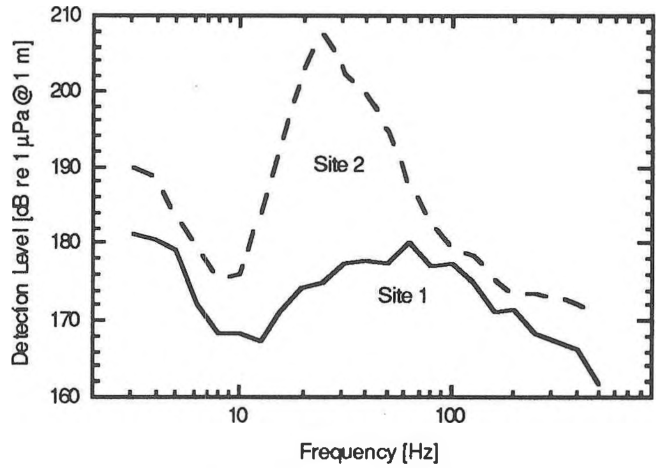

Fig. 4. Hypothetical Detection Level.

concept of "optimum frequency of propagation" has limited use in a passive detection scenario, unless the noise spectrum is flat.

4. THE WAY AHEAD

Although DREA has learned much about the shallow water acoustic environment in the course of our research, we have studied several topics insufficiently. The following list presents recommendations for future work.

- Most of our work has concentrated on single sensors at different depths; we need to more thoroughly investigate the performance of arrays of sensors whose signals are combined coherently.
- As there is renewed interest in active sonars of all types, we must do more work on surface and bottom reverberation in shallow water.
- We know little about the noise field and propagation conditions observed by geophone sensors—as distinct from hydrophones. We are moving into frequency ranges normally inhabited by seismologists and geophysicists, so it is natural for us to try their tools.
- Acoustic modelling capability must be advanced to admit 3-dimensional environments; most of the current range-dependent models still assume cylindrical symmetry about the source or receiver. Increasing complexity of models demands integration of models with both oceanographic and geophysical databases.

- We know little about modelling noise fields in shallow water. In the light of the discussion in the last section, perhaps what we really need is a capability to model Detection Level.

- As ever, our increasing requirement to interpret data and to predict sonar conditions generates a tremendous appetite for detailed environmental data, not only oceanographic, but geophysical. However, if we are not to expire under a mountain of information, we need to determine which are the *essential* parameters that govern the acoustic conditions *that matter*.

Our progress to date has benefited from close cooperation between experimental and theoretical efforts. Often the experimentalist will challenge the modeller with an apparently unexplainable data set that leads to the development of new modelling techniques. By the same token, the theoretician may discover some logical consequence of a model or theory that requires validation—or disproof—by a carefully designed experiment. This should not need to be stated in a scientific journal, but in the modern way of managing and budgeting our research it can often be forgotten.

5. CONCLUSIONS

DREA has made significant progress in understanding the physical mechanisms governing the acoustic environment, especially the role of the seabed. An important lesson learned was that passive detection is governed by the sum of transmission loss and ambient noise level, which varies from site to site much less than each component considered separately. The way ahead should include: experimental studies of array performance; environmental acoustic measurements relevant to active sonar; bottom-mounted sensors (including geophones); and integration of oceanographic and geophysical databases with sonar models in three-dimensional environments.

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