SYNTHESIS OF WAVE FIELDS IN AN ARCTIC ENVIRONMENT: DESCRIPTION AND APPLICATIONS.

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1 INTRODUCTION

OSIRIS [1], a recently developed programme, for modeling of underwater transmission loss efficiently handles arbitrary horizontal layering of both fluid, elastic and transversely isotropic layers, and thus represent a realistic Arctic environment. The elastic effects of both ice and subbottom are taken into account. It is known that local deviations from the ideal environment such as ice keels can cause a significant effect for the wave propagation. Such deviations can be modelled very efficiently by the boundary element method based on Green's function for a layered media [2].

For studying wave propagation in general these programs can be used with advantage. As an example seismic exploration in an environment with a plane ice–cover is discussed and the capability to analyse waves scattered from an opening in the ice is investigated.

Two applications concerning sound transmission in an Arctic environment are presented. The first example illustrates prediction of ship generated noise on a seismic hydrophone array. The source strength generated by the propeller and machinery of a seismic ship operating in an Arctic environment can be determined by measurements or predictions. However, the noise measurable on a seismic hydrophone array will depend strongly on the array transmission loss influenced by parameters such as water depth, velocity gradients in the water, ice–cover, subbottom geology and hydrophone array configuration. By using *OSIRIS* it is possible to predict the influence of these parameters on the sound transmission loss and thereby predicting the influence of ship noise on the seismic shot record. The second example illustrates use of sound propagation predictions in the assessment of environmental noise caused by shipping or offshore activities in an Arctic environment. The underwater noise generated by man–made sources such as ships or drill rigs influences the acoustic environment on which especially marine mammals are very dependent. A computerized exposure programme has been developed which combines the effect of source strength, sound transmission loss and ambient noise.

2 THEORY

2.1 THE DIRECT GLOBAL MATRIX METHOD

The direct global matrix method is a general method for elastic wave propagation problems in layered visco–elastic media developed by Schmidt and Co-workers [3, 4, 5, 6]. The method is also available as the commercial code *OSIRIS*, [1]. The medium is considered as a stack of homogeneous visco–elastic layers with visco–elastic half–spaces at the top and at the bottom. For a given

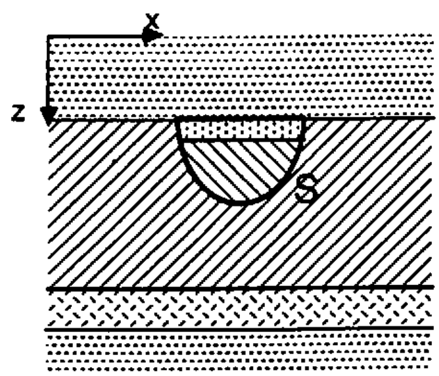

Figure 1: A horizontally stratified ocean seismo-acoustic environment is interrupted by a region of different properties, bounded by the surface S and stratified as well.

frequency the solution is represented as integrals over all horizontal wavenumbers. This is accomplished by use of a suitable integral transform, the Fourier transform for cartesian coordinates and the Hankel transform for cylinder coordinates. Within each layer the entire solution is represented as the sum of two contributions: 1) A general solution to the homogeneous equations represented in terms of integral transform functions, and 2) A contribution from a particular solution containing the sources associated with that particular layer, but in general not satisfying any conditions at the interfaces.

The solution of the displacement components, velocity components or stress components at a location (r, z) is obtained by inverse Hankel transform of the wavenumber function. The integration involved in the inverse Fourier or Hankel transform requires careful attention to a large number of computational details [6, 1]. For efficient integration an adaptive numerical integration scheme is applied [7, 1].

The displacement components, the velocity components or the stress components are obtained in the frequency domain. For seismic modelling the time response is found by convolution of the response with a wavelet.

2.2 THE BOUNDARY ELEMENT METHOD

The problem under consideration is outlined in Figure 1. A range independent ocean environment bounded at the top by a possible ice cover and below by an elastic stratified bottom, is assumed to be interrupted by a local deviation from the ideal, horizontal stratification, in the following referred to as a *facet*. Such facets can be ice keels or grooves in an Arctic ice–cover or sea mounts and diapirs in the ocean bottom. To enable analysis of the forward and backward scattering and reverberation introduced by such facets, we assume the facet to be sufficiently local to be enclosed within a surface S, enclosed by a horizontally stratified environment. The inner region is assumed to be horizontally stratified as well, but it could be of any composition, provided a mathematical/numerical model for its dynamic behavior is available. Thus, the inner region could be modeled by a finite element method, for example. The facet is assumed to have infinite extent in the out of plane direction and only line sources parallel to the facet will be considered, allowing for a 2-dimensional plain strain formulation of the wave equation.

The boundary element method is based on Green's theorem for an elastic media. By assuming that both the interior and exterior domains are plane stratified, the wave field can be expressed in terms of a boundary integral along the surface of the facet, provided the Green's functions are chosen to be the ones satisfying all boundary conditions in the stratifications. The integral around the facet is then discretized to obtain a system of linear equations, describing the distribution of displacements and tractions around the boundary of the facet. Each element in the equations is here a double integral over the geometric element and over wavenumbers. By interchanging these integrals and assuming a linear variation of the physical variables an analytical integration along each element is possible. This reduces the dimension of the integral by one. Solving the system of equations yields the set of displacements and tractions along the boundary. The theory is described in Gerstoft and Schmidt [2].

3 EXPLORATION IN A PACKICE ENVIRONMENT

During a recent EEC project the possibilities of extending the seismic exploration to an Arctic environment have been investigated. As part of this project the effect of various ice–covers has been investigated, [8].

3.1 PLANE ICE–COVER

For exploration in an Arctic environment one question is how to perform the collection of the data. A natural way would be to place geophones on the ice, and another concept is to use a submarine for towing the seismic cable. The seismograms for those two methods are presented in Figure 2 for an semiinfinite water column and an ice cover of 4 metres. The wavespeed for the water is 1500 m/s and the ice has a compressional wavespeed of 3000 m/s and a shear wavespeed of 1600 m/s, the ice attenuation is $1dB/\lambda$ and $0.5dB/\lambda$ for the compression and shear wave, respectively. The source is a placed at 30 metres depth with a 3-loop Ricker wavelet signature with a centre frequency of 20 Hz. The receivers are placed at a range from 300 to 1300 metres.

For the receiving hydrophone below the ice at a depth of 30 metres, Figure 2 a), the compressional head wave from the ice is seen as the first arrival and secondly the direct arrival from the source is seen. For the geophones on the ice recording vertical velocity, Figure 2 b), the flexural wave are dominating the later part of the seimogram. The flexural waves are seen as the waves of a relatively high frequency for the first arrivals and thereafter seen as waves of less and less relative frequency with time. This is due to the dispersion of the flexural waves in the ice–cover. For an ice cover of 4 metres and a wave with the dominant frequency of $20[Hz]$ the wave speed of the fundamental flexural wave can be estimated to about $c = 1000[m/s]$. The reflections from a subbottom will arrive at about the same time as the flexural waves and thus cause serious difficulties in the processing of the data, [9]. Due to the evanescent nature of the flexural waves these are very weak for the hydrophones in the water.

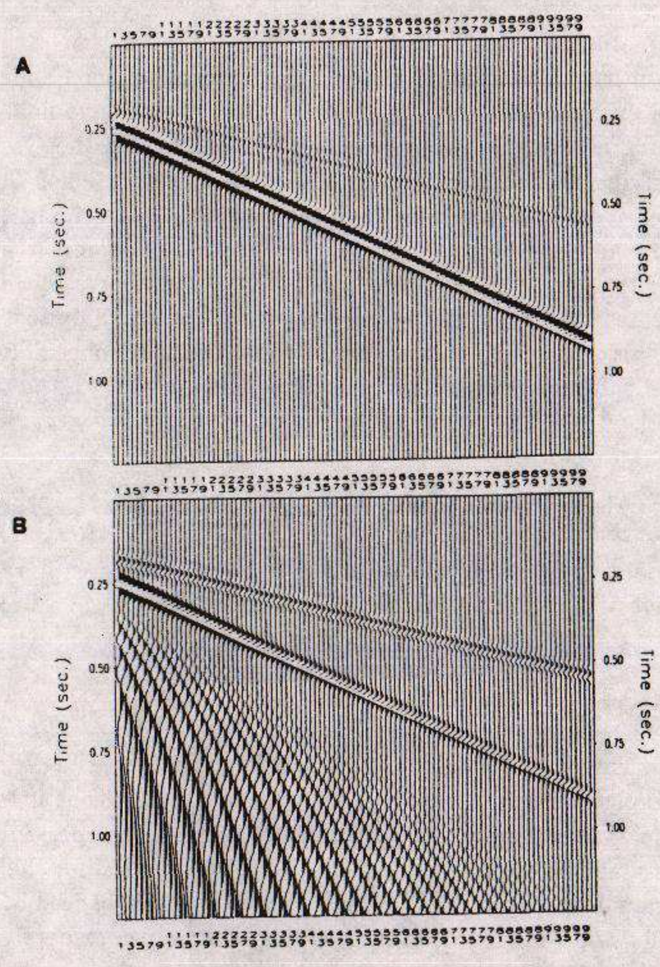

Figure 2: Seismogram for a plane ice-cover, the range is from 300 to 1300 metres and a range scaling has been applied. a) Hydrophones 30 meters below the ice and b) geophone placed on the ice recording vertical velocity.

3.2 A CAVITY IN A PLANE ICE-COVER

The present example is aimed at understanding the effect of an open lead or a cavity in an otherwise regulary stratified environment. For modelling of this the boundary element method is efficient as only the deviation from the ideal environment has to be discretized, see section 2.2.

The model is the same as in the previous example, but with a circular cavity with a radius of 4 metres at a range of 400 metres and receivers placed at 200 to 600 metres from the source. The pressure is shown as seismograms in Figure 3. The scattering effects from the cavity are seen to be of a very low amplitude. For investigation of the scattering effects the seismograms for the scattered field at two different locations have been computed. The seismograms are shown in Figure 3 b). A gain has been applied to the seimograms to show the wave phenomenon in the scattered field. At the under side of the ice-cover all the scattered field is nearly seen as a

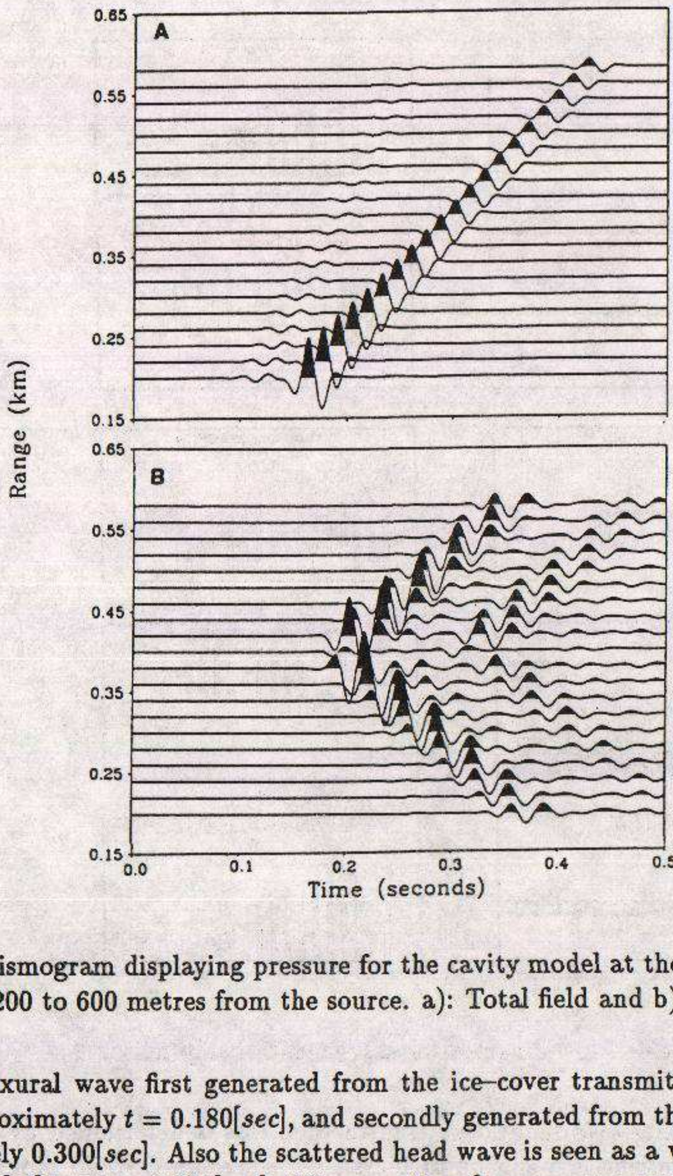

Figure 3: Seismogram displaying pressure for the cavity model at the underside of the ice–cover at range from 200 to 600 metres from the source. a): Total field and b): Scattered field.

scattered flexural wave first generated from the ice–cover transmitted compressional wave, first seen at approximately $t = 0.180[sec]$, and secondly generated from the direct incident wave seen at approximately $0.300[sec]$. Also the scattered head wave is seen as a very low amplitude wave front at range $250[m]$ at time $0.250[sec]$. Waves scattered as pressure waves into the water are present as well. The same scattering is seen from the direct incident wave as well.

4 SHIP NOISE

When evaluating the underwater noise generated by various shipping activities it is essential to know the free field monopole source strength. Investigations on ship noise are normally performed by measurements of the noise received at a distance from the ship. In order to obtain the source strength it is necessary to correct the measured noise with the sound transmission loss occurring

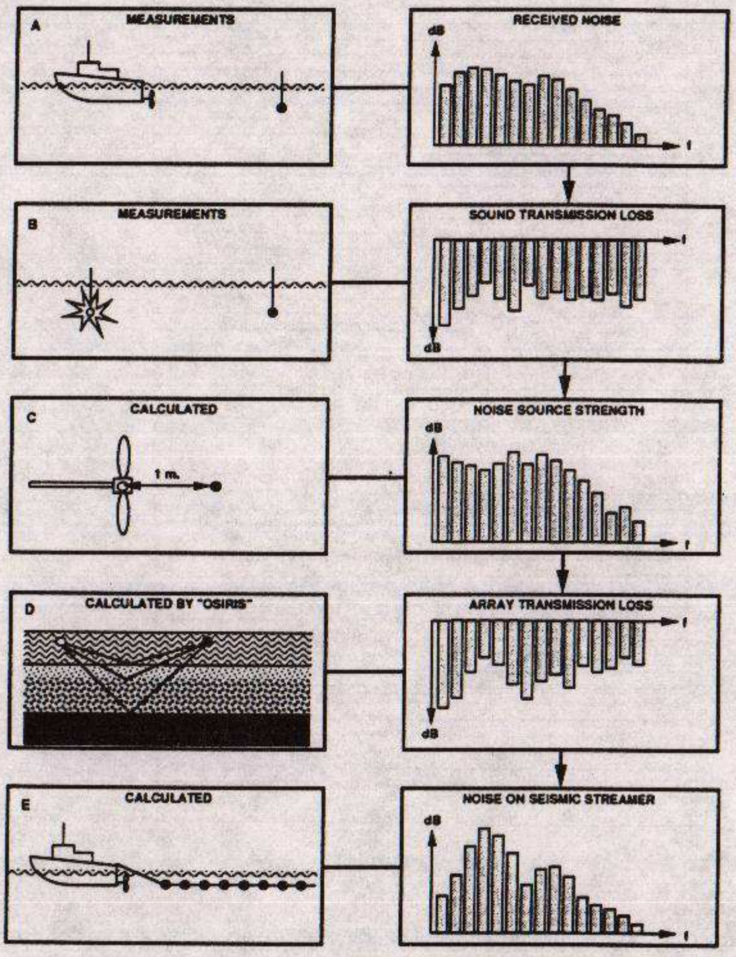

Figure 4: Flow diagram for assessment of ship noise.

at the actual measurement site. Normally this transmission loss is determined by measurements but when this is not possible, the loss can be predicted by using the *OSIRIS* programme. When the noise source strength of the ship is known, it is possible to predict the noise received from the ship at various other locations as the sound transmission can be modelled by the *OSIRIS* taking into account the different water depths, sound speed profiles, subbottom geology etc.

A special application of this procedure is evaluation of ship noise expected on seismic arrays, see Figure 4. In such an investigation, the underwater noise generated by the ship is measured with an omnidirectional hydrophone at a distance from the ship (A). After this, the sound transmission loss is measured at the same location (B) by means of a controlled calibrated source signal and a receiver at a distance. A free field monopole source is obtained by removing the surface reflection in the digitized time signal recorded from the controlled source. By adding the transmission loss to the

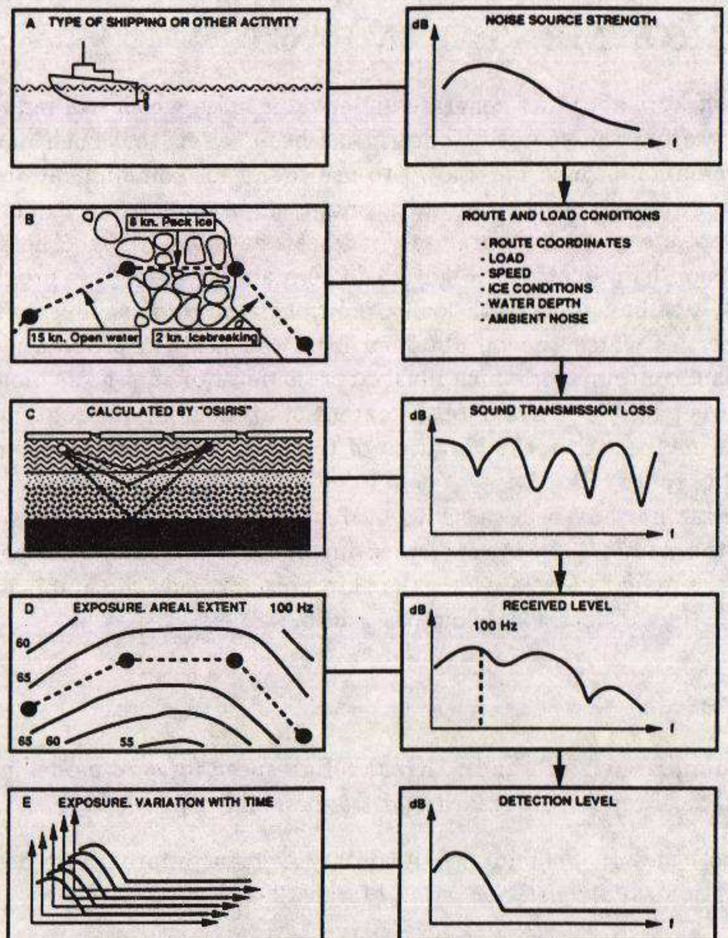

Figure 5: Flow diagram for noise exposure model.

recorded ship noise the source strength of the ship is found (C). Now it is possible, by application of *OSIRIS*, to calculate the ship noise at other locations and received by different hydrophone array geometries (D). The array transmission loss will depend on parameters such as: water depth, sound velocity profile, subbottom geology, streamer depth and hydrophone grouping. By subtracting the array transmission loss from the source strenght of the ship, the expected ship noise measured on the seismic streamer can be predicted (E).

When a seismic company wants to convert an existing ship (e.g. an old trawler) into a seismic survey vessel, it is possible by simple measurements and application of *OSIRIS* to predict the expected ship noise measurable on a seismic hydrophone array durring future use. In this way it is possible for the seismic company at an early stage to evaluate the suitability of the vessel and to determine the costs of possible noise reducing measures.

5 ENVIRONMENTAL IMPACT

Shipping or offshore activities generate underwater noise which will influence the acoustic environment far away from the source. Concern has been raised that such underwater noise may affect the marine mammals which are known to use sound for communication and navigation. In order to evaluate the impact on the natural acoustic environment due to planned shipping or offshore activities, a noise exposure programme has been developed [10]. The principle of the prediction of noise exposure is indicated in Figure 5. The main input for this programme is the noise source strength (A), a sailing route with load conditions and ambient noise levels (B) and sound transmission properties which can be obtained from the *OSIRIS* programme (C). The output of the programme is a contour plot which illustrates the level of ship noise along the shipping route (D). In this way it is possible to evaluate the extent of areas along the route where the ship noise might affect the marine life. Also, the variation of the noise with time can be plotted for an observation point along the route (E).

This programme has been used to evaluate the acoustic impact on marine mammals from activities in the Arctic, [11]. As indicated in Figure 6 the results of the calculations can be used to illustrate the extent of area where the ship noise exceeds the ambient noise and the noise level variation with time at locations along the route.

References

[1] O. Vilmann, P. Gerstoft, and S. Krenk. High-speed forward modelling in seismic data processing. Technical report, Ødegaard and Danneskiold-Samsøe, 1989.

[2] P. Gerstoft and H. Schmidt. A boundary element approach to ocean seismo acoustic facet reverberation. *J. Acoust. Soc. Am.*, March 1991.

[3] H. Schmidt and F.B. Jensen. A full wave solution for propagation in multilayered viscoelastic media with application to Gaussian beam reflection at fluid-solid interfaces. *J. Acoust. Soc. Am.*, 77:813–825, 1985.

[4] H. Schmidt and J. Glattetre. A fast field model for three-dimensional wave propagation in stratified environments based on the global matrix method. *J. Acoust. Soc. Am.*, 78:2105–2114, 1985.

[5] H. Schmidt and G. Tango. Efficient global matrix approach to the computation of synthetic seismograms. *Geophys. J. R. Astr. Soc.*, 84:331–359, 1986.

[6] H. Schmidt. SAFARI: Seismo-acoustic fast field algorithm for range independent environments. user's guide. SR 113, SACLANT ASW Research Centre, La Spezia, Italy, 1987.

[7] S. Krenk, P. Gerstoft, and O. Vilmann. Computational aspects of synthetic seismograms for layered media. In *59th meeting of Society of Exploration Geophysicists*, pages 1086–1089, 1989.

[8] O. Vilmann and P. Gerstoft. The effect of ice-covers on seismic wavefields. Technical report, Ødegaard and Danneskiold-Samsøe, 1990.

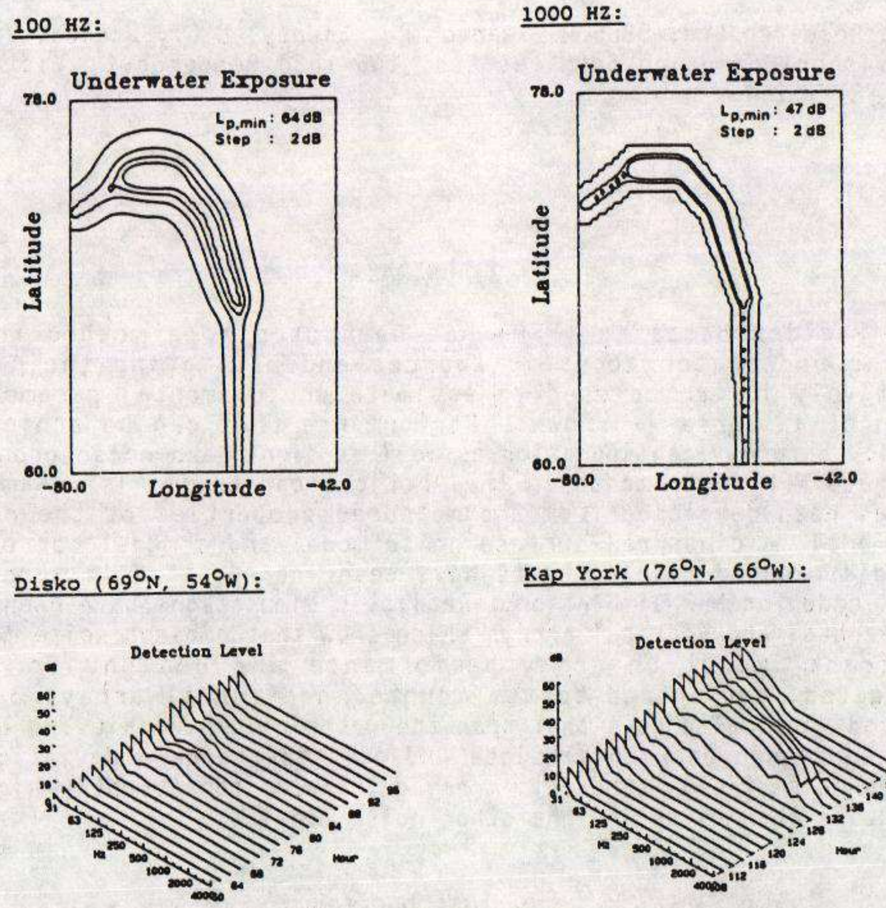

Figure 6: Examples of predictions from the exposure programme.

[9] C. A. Rendleman and F. K. Levin. Seismic exploration on a floating ice sheet. *Geophysics*, 90, 1990.

[10] L. Thiele, A. Larsen, and O. W. Nielsen. Underwater noise exposure from shipping in baffin bay and davis strait. Technical report, Ødegaard and Danneskiold-Samsøe, 1990.

[11] R. A. Davis, W. J. Ricardson, L. Thiele, R. Dietz, and P. Johansen. State of the Arctic environment report on underwater noise. Technical report, Finnish Initiative on Protection of the Arctic environment, 1990.