Modelling sound propagation under ice using the Ocean Acoustics Library's Acoustic Toolbox

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ABSTRACT

Acoustic propagation in the Arctic and Antarctic is largely characterised by the presence of a highly variable ice canopy. To model sound in these environments requires both a way of effectively representing the ice layer and modelling its effect on signal transmission. The Ocean Acoustics Library has a powerful open source Acoustics Toolbox that contains Fortran code for running Ray, Normal Mode, and Wavenumber Integration models. There are two parts to modelling a sea ice environment: modelling the ice as an elastic acoustic medium, and modelling the roughness of the ridging characteristics of the ice. This work considers the scenario of an Autonomous Underwater Vehicle (AUV) producing a survey under ridged sea ice. This specifies a range of interest of 10km and a frequency band of interest of 3kHz-13kHz. An overview of methods for modelling ice as an acoustic medium and as a ridged surface is provided, and the applicability of different propagation and ice models for this scenario is discussed. The scenario is then implemented as a specific test case for two example ice canopy profiles. The ice canopy profiles used are sea ice draft measurements recorded in the Arctic using an upward looking SONAR on a nuclear submarine. Beam and ray methods are the only computationally fast propagation codes for this frequency range and are included in the BELLHOP module of the Acoustics Toolbox. With these methods the options for including the elastic properties of the ice are limited and only include reduction in the coherent field on reflection. Two methods for including the ridging of the ice canopy are implemented, one statistically based and one using direct input of measured ice canopy data. The statistically based method uses Twersky boss scattering, and the direct method inputs the draft data as an altimetry file. Gaussian beam tracing using BELLHOP is run to generate ray trace and coherent transmission loss estimates of this environment. The advantages and limitations of these implementations are discussed with suggestions for future improvements to the Acoustics Toolbox to better model the ice scenarios outlined. The improvements identified from this review and test case are: the capability to include specific ice condition data where available, better consideration of the elastic properties of the ice in BELLHOP; and new statistical methods for modelling unknown variable surface boundaries that provide statistical distribution information as well as mean field values.

INTRODUCTION

Accurate sea ice volumes and under ice biology measurements are important inputs to global ocean climate and ecosystem models, and key indicators to monitor for change. With an increasing focus on climate science and change there is an increasing importance in measuring and monitoring what is happening under the ice covered oceans of the Arctic and Antarctic (Wadhams 2009). With advances in Autonomous Underwater Vehicle (AUV) capability the use of this technology in the ice environment is becoming more frequent (Jakuba et al. 2008; Kaminski et al. 2010; Wadhams and Doble 2008). AUVs operating in an open ocean environment use underwater acoustic communication for non-safety critical information and rely on their ability to surface and establish radio or satellite communication for critical situations such as navigation error or mission failure. In an under ice environment there is a far greater reliance on underwater communication as surfacing is no a longer option. Understanding and modelling acoustic propagation in an under ice environment is a key component in increasing safety and reliability in these deployments.

Typical Sound Speed Profiles (SSPs) in the Arctic and Antarctic produce an upward refracting sound environment that creates a sound channel that is continuously reflecting off the top boundary, usually an ice layer. To model propagation in this environment requires both the ability to create a realistic model of ice and the capability to incorporate the ice model within a framework for predicting acoustic propagation and transmission loss. The ice layer in a sea ice environment is a complex system made up of different ice types, thicknesses, and areas of ice deformation and ridging (Untersteiner 1986; Worby et al. 2008). This environment is highly variable with location, season and local weather conditions. The effect of this spatially and temporally variable ice layer creates a large variation in reliability of acoustic propagation that is also strongly frequency dependent. There are two main parts to including an ice layer in an acoustic model. The first is consideration of an ice layer as an acoustic medium and the second the inclusion of randomly shaped and sized perturbations cased by sea ice ridging. Once the ice is included in the acoustic model there is than the question of what propagation modelling technique is most appropriate. The Acoustics Toolbox (AT) (Porter, Michael (*Acoustic Toolbox*)) is an open source modelling tool that provides a selection of environment and propagation modelling tools within the one software framework. This work considers different methods for including an ice layer in the environment model of the AT, and evaluates which propagation and transmission loss techniques are appropriate with this ice environment.

There has been significant research into under ice sound propagation in the Arctic since the 1960s. This is due to the disputed nature of borders in this area, defence prerogatives such as submarine detection, the potential for natural resources, and the capability for long range propagation. The consequence of this is a body of research investigating the effect of an ice canopy on acoustic propagation at both low and high frequencies. Low frequencies have the potential for long range propagation, whereas high frequency signals suffer greater scattering and attenuation losses due to the roughness dimensions of the ice and the frequency dependence of its attenuation (Gavrilov and Mikhalevsky 2006; Kutschale 1969; McCammon and McDaniel 1985). For high frequencies ($>$ 15kHz) the report by the Applied Physics Laboratory, University of Washington (Applied Physics Laboratory 1994) provides a comprehensive section on acoustics in the Arctic. For low frequency there are many investigation into long range propagation that examine low frequency interaction with ice (Gavrilov and Mikhalevsky 2006; Kuo 1990; Kutschale 1969).

Compared to many of the long range propagation scenarios considered in the Arctic, communication systems for AUV deployment require relatively high frequencies (1-15kHz) and short ranges ($<$ 100km). Typical underwater acoustic modems operate between 8-13 kHz, with some modems reporting frequency ranges of 3 to 30 kHz (Freitag et al. 2005).

There are five main techniques used in modelling underwater acoustic propagation. Ray theory, Normal Mode, Multipath Expansion, Wavenumber Integration (WI) or fast field, and Parabolic Equation(PE) (Etter 2001). Etter provides a review paper that summarises modelling and simulation reported up to 2001 (Etter 2001). For higher frequency work ray tracing provides the fastest solution with a minor compromise to accuracy (Jensen et al. 1994).

This paper provides a review of modelling ice, first as an acoustic medium, and then as a variably ridged layer. The techniques available in the Acoustics Toolbox are then introduced and some simple test scenarios evaluated. A discussion on the applicability of the current tools available in the acoustics toolbox and its suitability as a tool to model an ice environment is then presented. The Acoustic Toolbox is an open source library that can be used to model acoustic propagation and loss. Understanding how it can be used to model ice will improve the reliability of communications systems operating in an under-ice environment and contribute to the safety and risk profiles of AUV survey work in this environment.

MODELLING SEA ICE

The formation of sea ice is dictated by the weather (meteorological) and water (hydrographical) conditions at time of formation and through its life cycle. These conditions affect the temperature, salinity and texture of the ice as it is formed and as the ice grows in thickness the different layers tell the story of the conditions under which it was created (Eicken 2003). The ice first forms as slush, then forms into small distinct plates then larger floes that are further affected by environmental conditions and deformed to create a ridged ice environment. This process means that sea ice is a range and time varying surface layer.

The majority of the experimental work to date is based on Arctic sea ice conditions. Sea ice in the Antarctic is generally formed under more dynamic weather conditions and the ice growth cycle is different to the Arctic (Eicken 2003). As most of the acoustic experimental work is based on Arctic ice, in this paper it is assumed that the properties being referred to are for Arctic ice unless specifically qualified as Antarctic.

A sea ice model takes as input the properties of the ice and supplies information to a propagation model such that it can calculate the effects of this boundary layer. A description of ice for a model could be:

- The acoustic properties of the ice
    - Ice density (ρ)
    - Compressional wave speed and attenuation (C_p, A_p)
    - Shear wave speed and attenuation (C_s, A_s)
- Seasonal properties of the ice
    - Temperature profile
    - Salinity profile
    - Air/ice temperature
    - Ice growth stage
- The physical(shape) properties of the ice
    - Thickness,
    - Ice-water roughness
    - Ice-air roughness,
    - Ridging statistics

With outputs of the ice model being:

- Reflection losses
- Phase change

Sea ice as an acoustic medium

The dynamic formation of sea ice means that sea ice, as an acoustic medium, has a variable vertical profile that is dependent on the conditions under which it is formed. The following sections review the different aspects of this life cycle and compositional variability in undeformed ice and evaluates the effects of these properties on acoustic models.

A large amount of sea ice is formed and decays within a seasonal winter, summer cycle and is referred to as first year ice. Jezek et al (1990) describe the transition of the roughness of the surface of sea ice as it grows, beginning as slush from the collection of frazil ice through the growth of pure ice dendrites, a crystal that forms with a tree like form (Stanton 1986), that acts as a skeletal layer on the ice surface collecting salty brine pockets, to finally form a smoother more homogeneous surface. The bottom surface properties and reflectivity of the ice layer vary significantly between the forming, stable and decaying stages of the ice life cycle. Experiments by Jezek et al (1990) on the reflective properties of the bottom surface of growing ice using high frequency sound at normal incidence showed attenuation of sound interfacing with ice with dendrites to be five times greater than that of homogeneous ice, and ten times less than slush ice. Experiments by Garrison et al (1991) report an additional attenuation of 8-11 dB from growing ice with a skeletal bottom layer compared to solid ice. The effects of these dendrites, or skeletal layer, increase with the frequency of the incident wave (Yew 1987).

	Kuperman and Schmidt 1986	Yang 1994	Jensen 1994	Gavrilov 2006	McCammon and McDaniel 1985
Frequency [Hz]	47-100	80-160	50Hz	16-36	2000
Mean thickness [m]	3.9	2.2	4	(2, 3)	0.8
Water rms roughness [m]	1.9	-	-	(1.2, 1.8)	-
Air rms roughness [m]	0.6	-	-	(0.3, 0.45)	-
Comp speed (Cp) [m/s]	3000	3120	3500	3000	3593.4
Comp attenuation (Ap) [dB/λ]	0.5	0.76	0.4	0.45	0.068 [dB/m kHz]
Shear attenuation (As)[dB/λ]	2.5	0.05 [dB/m]	1.0	0.9	0.4 [dB/m kHz]
Shear velocity (Cs)[m/s]	(1500,1800)	1650	1600.0	1800	1809.9

Table 1: Geoacoustic Parameters of Arctic ice used in previous studies. Values given within brackets represent (winter, summer) when available

The temperature and salinity profiles of an ice layer affect the density and the porosity of the ice which then affects the elastic properties of the ice and the reflection loss of acoustic waves interacting with the ice (Applied Physics Laboratory 1994; Rajan 1993). Porosity and ice thickness are reported to have the largest effect on the acoustic properties of the ice (Yew 1987), with density remaining more stable (Hunkins 1960). Changes in ice thickness are reported to have a greater effect on reflectivity than salinity or temperature layering within the ice medium, with attenuation primarily a function of frequency and ice thickness. Attenuation is reported to increase linearly with frequency up to 100kHz (McCammon and McDaniel 1985), If the shear velocity is less than the speed of sound in water, a vertically polarised shear velocity, as reported by Kuperman and Schmidt (1986) occurs, at which point the air-ice boundary also becomes significant to the model. Hunkins (1960) measured and analysed longitudinal and transverse waves within an ice sheet. These flexural waves are understood to interfere with compressional waves and the acoustic field in the water close to the ice boundary (Jensen et al. 1994, p443). McCammon and McDaniel show that the elastic properties of the ice play an important role in attenuation of a plane wave on an ice surface at both high and low frequencies (McCammon and McDaniel 1985).

Given all this variability, how do we model ice as a acoustic medium? The model needs to provide a means of establishing reflection loss and phase change of plane waves on the water/ice boundary. Directly measuring the reflection loss of an ice environment is the most accurate way to model reflection loss for a given environment and frequency. Reflection Coefficients (R_c) can be measured using Matched Field Processing (MFP) on a horizontally propagating signal (Livingston 1989), or varying the angle of incidence of an upward looking transponder (Applied Physics Laboratory 1994). The applicability of this measured value is dependent on the angles of incidence, the frequency and specific environment under which it is measured. The problem with using measured reflection coefficients for modelling is that they are only relevant for modelling the ice that the measurement was made with and can not be extrapolated to other environments. Experimentally derived reflection coefficients and the methods used to produce them are given in Livingston (1989) and Garrison (1991).

An alternative to directly measuring transmission loss is modelling ice as an acoustic medium using estimates of its acoustic parameters. This is more complicated but more readily extrapolated to different ice conditions and the complexity of the model can be changed depending on what measured or estimated properties of the ice are available as input. A simple example of changing the ice model with ice growth conditions is shown in Jensen et al (1994), where older ice is described as a homogeneous elastic medium with compressional speed 3500 m/s and shear speed 1800 m/s and slush ice as a fluid medium with a compressional speed of 3500 m/s. A more complex model is used by McCammon and McDaniel (1985) who model ice as a multi-layered elastic solid bounded on both sides by a fluid half space, and Yew (1987) who models it as a ‘transversly isotropic brine saturated porous medium’. Modelling ice as a multi-layered medium allows for the inclusion of a skeletal growth layer and surface snow as well as variability with the ice itself.

The acoustical properties to describe an ice layer can either be found through specific experiments to measure the sound velocities in the ice or through processing of temperature and salinity measurements. In the literature a range of different acoustic parameters for ice are reported and used. A selection of these is shown in Table 1 with more reported parameters shown in Desharnais (2003). Acoustic parameters reported from field measurements are found using techniques such as cross hole tomography (Rajan 1993), freezing metal rods into the ice and hitting them as a sound source, digging pits and cores in the ice and hitting the side with hammers or inserting sound sources, and explosive source experiments. The method for calculation of the acoustic parameters from temperature and salinity are summarized in the report by the Applied Physics Laboratory for the US Navy (Applied Physics Laboratory 1994). It summarises the process of calculating density and porosity from temperature and salinity put forward by Biot, Cox and Weeks then provides equations to compute compressional and shear speeds and bulk moduli put forward by Williams and Francoise (1994) and attenuation as a function of frequency and temperature put forward by McCammon and McDaniel (1985). Livingston (1989) derives the reflection coefficients for a particular test site experimentally using Matched Field Processing and compares this to different modelling techniques that model the ice using acoustic properties and finds the direct measurement significantly more accurate. This work is looking at ridged conditions and as such is describing the effective reflection coefficient given the ice conditions as an acoustic medium combined with the effects of the specific roughness of the ice that the experiment was carried out under.

Modeling ice with ridges

Sea ice ridging is formed by the shearing and compression of ice floes pressing out ice blocks below and on the surface of the ice

(Marchenko and Makshtas 2005). Shear ridging creates smaller chunks of ice with more of a ground up appearance while pressure ridging creates a collection of more discrete blocks of different shapes, sizes and orientations (Applied Physics Laboratory 1994). While ridging affects both the top, referred to as the ridge sail, and bottom referred to as the keel, of the ice sheet this is not symmetric and the surface once formed undergoes significantly different weathering than the bottom formation. While it is not symmetric there is correlation between top and bottom geometries that can be used to estimate bottom roughness from surface features (Diachok 1976; Gavrilov and Mikhalevsky 2006). Measurements have been made of keel to sail heights as a ratio but this fluctuates with area and conditions (Applied Physics Laboratory 1994). As sea ice undergoes many deformations the underside becomes a continuously rough surface in which the exact definition of a keel, as opposed to the other roughness of the surface, varies (Rothrock and Thorndike 1980). One common definition used to define a keel as opposed to a random roughness is that a keel is a keel if it has a trough on one side that is less then $(keeldepth + 2.5)/2$ m deep (Applied Physics Laboratory 1994). This is fairly arbitrary and only useful if comparing statistics with other models that use the same definition.

Ridged ice can either be modelled implicitly or explicitly, in that it can be modelled as an overall acoustic effect or as a set of physical ridges. The ridged ice layer is made up of both the plate like backing of the acoustic medium discussed in the previous section and a variable scale of roughness features. The purpose of modelling the roughness of the underside of the ice is to establish the effect of the ridging on a transmitted signal. There are two main approaches to modelling ridged ice used in the literature. One is to treat it as a statistically rough boundary problem, the other is the inclusion of discrete or statistical keel features, based on geometric approximation. As the exact size and shape of the ridges in the propagation path are rarely known they are usually modelled by statistics, preferably derived for the location and season that is being investigated. Data used to create and evaluate these statistical models of ridging are upward looking sonar data from submarines, moored sonar systems, and bottom roughness estimates given surface conditions. Models of ice vary from precise studies on the scattering and effects of single keel structures through to imprecise estimates of a general dB/km with frequency (Applied Physics Laboratory 1994). An example of statistical inclusion considering the environment as containing a discrete set of keels is put forward by Diachok (1976) who used randomly oriented infinitely long half ellipses with width and depth variables.

PROPAGATION MODELS

There are three main modelling types included in the Acoustics Toolbox: Ray; Normal mode; and Wavenumber Integration (WI). AcTUP (Duncan 2006) provides an integrated graphical interface combining the Acoustics Toolbox and RAMS Parabolic Equation (PE) models. There are three main attributes of an ideal model for a variable ice canopy: inclusion of the elastic properties of the ice layer including absorption and refraction; inclusion of canopy roughness; and be able to be computed for the frequency range of interest at a reasonable speed.

Etter (2001) in his review of acoustic modelling tools describes Kapoor and Schmidts technique for modelling ice as an infinite elastic plate with perturbations as the 'canonical model'. Alternatively Jensen (1994, pp. 240-245) states that 'Ever since the pioneering work of Kutschale the wavenumber integration approaches have provided a unique tool for modelling under-ice propagation in the arctic ocean.' The finite-difference (FD) and boundary element methods (BEM) have a much better prediction of scattering and include the elastic properties of the ice (than other techniques) but the processing time is prohibitively large (Jensen et al. 1994). Kutschale's wave number integration technique is highly appropriate for long range low frequency work as it models the wave train that forms in this situation (Kutschale 1969) but is not usable for higher frequency work. When the acoustic wavelength is small compared to environment dimensions then ray based modelling is good for calculating the effect of reflection on transmission loss (Diachok 1976). The acoustic wavelength for a 3 kHz signal in water with a sound speed of 1440 m/s is 0.48 m. For ice features with dimensions large compared to 0.48 m ray tracing will provide an accurate model for transmission loss. Jensen et al write the following on the selection of propagation model

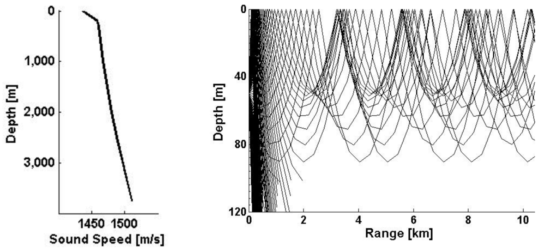
> For high frequencies, ray theory, the infinite frequency approximation, is still the most practical, whereas the other four model types (wavenumber integration, normal modes, parabolic equation, finite difference/element) become more applicable below, say a kilohertz

(Jensen et al. 1994, p56). There choice of a kilohertz suggests an ice canopy with features large compared to a reference of 1.4 m.

There is no single ideal modelling method in the Acoustics Toolbox that is able to capture all of the parameters needed for modelling ice when looking at this frequency range. As the frequency range of interest for AUV work is kilohertz, ray tracing is the only feasible technique. The downside to using this technique is the poor consideration of the elastic effects of the ice as a medium.

Test Case

The scenario being considered is that of an AUV undertaking a survey under ridged Arctic ice that is no longer growing and has acoustic parameters used by McCammon and McDaniel (1985) as shown in Table 1. A lower limit frequency for this scenario is 3 kHz and a horizontal range up to 10km is used. The input parameters used for this experiment are shown in Table 2 with the sound speed profile and a BELLHOP ray trace using this profile with a flat surface shown in Figure 1. Two methods of including the ice layer were



(a) Sound speed profile (b) Ray Trace

Figure 1: Typical Arctic sound speed profile and corresponding ray trace if the surface is modelled as perfectly smooth

tested: specification of discrete ridges using altimetry files and the Twersky scatter effects outlined in (Diachok 1976). While there was code for including Twersky scattering losses in the Acoustics Toolbox it was only included in the Kraken part of the Toolbox which uses Normal Modes, and had been unlinked and partially retired. The Twersky effects included here are done so by implementation of Diachoks formula for reflection loss shown in Eqn 1 into the BELLHOP program.

$$R = \left(\frac{1 - xNd/\sigma}{1 + xNd/\sigma} \right)^2 \tag{1}$$

where R is reflectivity, x is a correction factor for the half-ellipse that is assumed to be one, N is the ridge density per kilometer, d the mean ridge depth and sigma the incident angle. This equation is valid for $kd > 1$ where k is the wavenumber. Diachok provides a second formula for cases of $kd < 1$ but it is not applicable to this test scenario. By using this equation the reflection loss is dependent on incidence angle, ridge density and mean keel height and keel width can be ignored.

The ridging statistics and profiles were made from two sample 10km sections of upward looking sonar data recorded using a submarine in the Arctic in August 1998 (University of Colorado). These profiles are shown in Figure 2 with what is considered a keel identified with a *. A keel was defined as a peak that was greater than 2.5/2 its local minima. This is quite heavily ridged ice with keel densities of 10.2 and 16 ridges/km and mean ridge heights of 3.4 and 3.7 m. These statistics provide the input required for the Twersky specification in BELLHOP and the profiles were converted into altimetry files for the discrete ridging input.

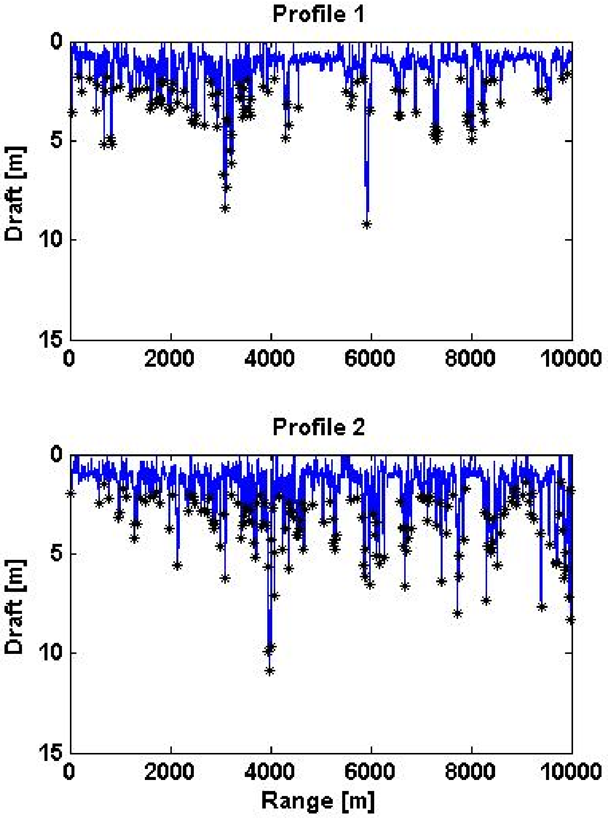


Figure 2: Two sample ice draft profiles taken in the Arctic in August 1998, stars are identified keels

Parameter	Value
Frequency	3kHz
Range	10km
Source Depth	50m
Receivers	100 (3m - 90m)
Beam Type	Gaussian
Transmission Loss	Coherent
Beam Fan	-30, 30 degrees

Table 2: BELLHOP Inputs

The Acoustics Toolbox was run with the following configurations:

- No ridging parameters (Ray and CTL)
- Twersky ridging parameters for profile 1,2 (CTL)
- Altimetry defined ridging parameters for profile 1 and 2 (Ray and CTL)

The results from the modelling are shown in Figures 3, 4, 5.

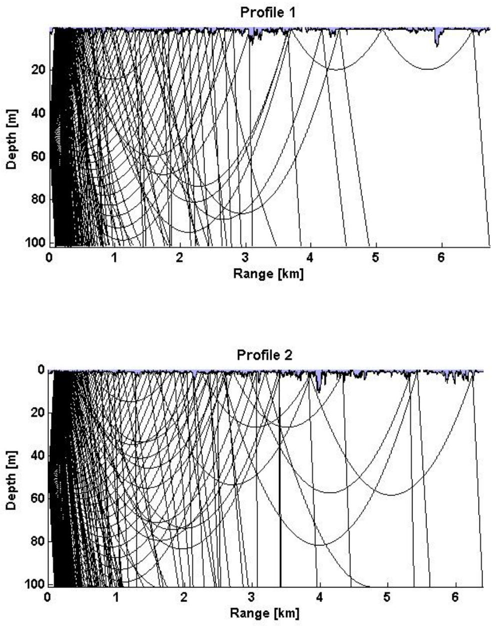


Figure 3: BELLHOP ray trace results for Arctic profiles 1 and 2

DISCUSSION

The ray trace diagram of Figure 1 shows an effective surface sound channel as a result of the sound profile, as opposed to those shown in Figure 3 where this channel has been disrupted with the inclusion of ridging. The affect of the ridging on transmission loss can be seen in

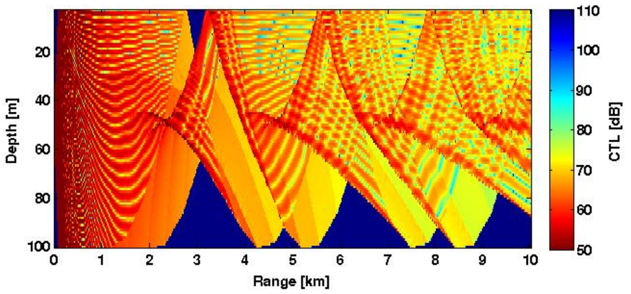
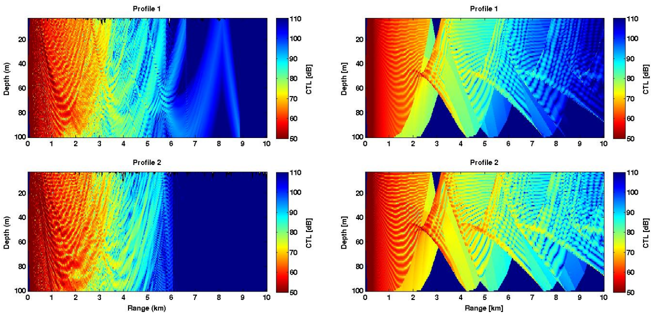


Figure 4: BELLHOP coherent transmission loss results for a perfectly flat surface specified as an acoustic half space with ice parameters



(a) Altimetry Input (b) Twersky Input

Figure 5: BELLHOP coherent transmission loss results for Arctic profiles 1 and 2 specified using Altimetry files and Twersky scattering

the difference between Figure 4 and Figure 5. Transmission loss diagrams using the Twersky approximation method and direct entry of altimetry are shown to provide examples of the output produced for these two techniques. As the Twersky method is statistically based and the altimetry input is discrete it is not valid to compare the techniques based on these limited results and the outputs are shown only to provide examples of what the techniques produce. One method to get a comparison between these two methods would be to run a Monte Carlo simulation combining the results for a large set of ice profiles with the same statistical properties, density and mean height, that have been put into the Twersky method. The Acoustics toolbox was able to run all of these simulations in the order of seconds with the time taken varying with the number of beams used to represent the signal. This fast time means that it is an appropriate tool for running simulations that run the program large numbers of times, such as Monte Carlo modelling. The disadvantages of using BELLHOP are that it does not accurately model ice as an elastic medium. It does not include flexural or head waves and does not consider many of the effects of the shear wave and scattered field. It is possible to include the reduction in coherent field from scattering in BELLHOP, through creation of reflection coefficients that account for this additional loss, but this is only one of the effects of scattering. Creation of reflection coefficients for elastic media is easiest done through the Bounce program that is a part of the Acoustics Toolbox. Bounce could be used to create a more accurate reflection coefficient that is based on a multi-layered ice model. This program could be extended to take in salinity, temperature and growth stage data in its calculations. This approach is limited as Bounce only considers a range independent medium and as such the reflection coefficients it calculates are for a single ice thickness and profile. Modelling of the keels as half ellipses is not based on current information known about ridge geometries (Timco and Burden 1997). Different statistical methods for including ridges using different correlation values between ridge height, width, shape and distribution information should be explored.

CONCLUSIONS

Sea ice is a strongly varying acoustic medium. The reflection loss of ice can be included in acoustic models through direct measurement of the reflection loss in the field, or including an ice layer as a part of the acoustic model by estimating acoustic parameters. The advantage of modeling ice by its acoustic parameters rather than a measured reflection coefficient is the ability of this technique to be applied to new situations and be simplified or expanded depending on the information available. The contrasting advantage of using a directly measured reflection coefficient is that it more accurately models the sound channel being investigated, but is limited to the frequency and incidence angles for which it is measured.

In AUV experiments it is unlikely that the acoustic channel will be measured before the first deployment, making the acoustic parameters of ice the only way to predict the conditions. It is possible that if multiple deployments were undertaken in similar ice conditions the acoustic signals sent and received during the initial experiment could be processed to establish a reflection coefficient for the given conditions that could be used in planning of subsequent missions. To make the acoustic parameters used for modelling ice as accurate as possible, ice temperature and salinity should be inputs to a realistic model, allowing the acoustic properties of the ice to vary with location and conditions. The choice of propagation modelling technique for an ice covered environment is mostly dependent on frequency and processing time. To get the most accurate model of acoustic interaction with ice Finite Difference of Boundary element methods provide the best solution for modelling the elastic and scattering effects. These methods are not feasible at higher frequencies where Ray tracing and Gaussian beam reflection loss models provide the only fast method for calculating signal loss and shadow zones. The advantage of a faster running model is that it is possible to consider representation of ridges in a statistical way that would involve multiple runs of the program such as a Monte Carlo simulation. Techniques such as Monte Carlo facilitate production of a statistical distribution as well as an average.

This review found that the Acoustics Toolbox has appropriate tools for basic under ice acoustic modelling at high frequencies. It further identified ways that it could be improved to include a more realistic picture of ice conditions and more appropriate output. Ray tracing is found to be the most appropriate propagation technique for fast modelling of an ice canopy. Current modelling was identified as missing inputs for specific ice conditions. The following ways to use and extend the Acoustics Toolbox to model ice more accurately are proposed: Ability to input ice information and calculate acoustic parameters; inclusion of a multiple ice layer model using Bounce; and development of a Monte Carlo ridge generation tool to get a better statistical picture of the probability distribution of acoustic signal transmission propagation and loss.

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