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ONR Code 32 Ocean Acoustics Core Project Final Report

**Improving predictions of mid-frequency sound propagation and
reverberation in a deep ice-covered ocean**

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Abstract

This one-year trial effort is aimed to investigate combined effects of critical variables of arctic environments, the roughness, elasticity, and layered structure of sea ice, as well stratification of water column (Arctic surface and sub-surface ducts). A hybrid approach is proposed that combines PE, Image Source, and Ray models, that allows analysis of sound intensity time series measured under ice at short and medium ranges. The approach is tested on two midfrequency acoustic datasets. The first one is comprised of ICEX14 data obtained using 3500Hz 5s-long CW pulses for fixed geometry of source and receiver at ~30m depths and ~720m range. The second one, considered for a trial analysis, is a much more comprehensive dataset collected during ICEX16 using mobile transmitters, various source-receiver ranges (0.3-10km), depths (45-183m), and transmitted waveforms (CW pulses and LFM sweeps). For both datasets, the spatial and temporal structures of multi-path propagation arrivals and reverberation caused by reflections and scattering from rough ice and bottom are analyzed, and results of model-data comparisons are presented.

Keywords:

deep arctic ocean, ICEX14 and ICEX16, mobile transmitters, rough sea ice and seafloor, arctic water stratification, multi-path propagation and reverberation, model-data comparisons.

Abbreviations:

ICEX14	Ice Experiment 2014
ICEX16	Ice Experiment 2016
APL-UW	Applied Physics Laboratory, University of Washington
NPS	Naval Postgraduate School
CW	Continuous Wave
LFM	Linear Frequency Modulated
PE	Parabolic Equation
TL	Transmission Loss
BSS	Bistatic Scattering Strength
GABIM	Geo-Acoustic Bottom Interaction Model
GAIM	Geo-Acoustic Ice-interaction Model

LONG-TERM GOALS

The goal is to investigate possibilities for improving predictions of mid-frequency sound transmission and reverberation in a deep ice-covered ocean at short and medium ranges. The project suggests developing a physics-based model that accounts for roughness of the seafloor and sea ice, and for the deep arctic ocean water stratification. The model will describe spatial and time-frequency structures of multi-path propagation arrivals and reverberation caused by reflections and scattering from rough ice cover and ocean bottom, will allow their quantitative analysis and model-data comparisons.

OBJECTIVES

The objective of this one-year effort is to suggest a trial model for analysis of acoustic data on midfrequency transmission under ice in a deep Arctic Ocean and provide its trial test on representative model-data comparisons. Two experiments performed in the Beaufort Sea are considered for the analysis and discussed. The APL-ICEX14 measurements were made using CW pulses for fixed geometry of source and receiver. The NPS-ICEX16 experiment was performed using CW pulses and LFM sweeps from mobile transmitters and spatially separated hydrophones at different combinations of source-receiver ranges and depths. For analysis of recorded timeseries, a modeling approach is suggested that considers several types of arrivals contributing to the received signal at different time intervals. The direct arrivals corresponding to nearly horizontal propagation are described using a hybrid approach that combines PE, Image Source, and Ray models. It employs a fast PE code for propagation in a stratified ocean with flat ice-free surface to account for effects of structure and dynamics of the arctic surface duct and then adds a field of an image source whose strength is defined by a complex reflection loss factor of the ice cover at small grazing angles. The direct signal is followed by reverberation coda that is modeled by bottom- and ice-bounced arrivals with corresponding reflectivity and scattering strengths at steep angles. Potential applications to remote sensing in ice-covered environments are discussed.

TECHNICAL APPROACH AND WORK COMPLETED

Midfrequency acoustic transmission in the ice-covered ocean, which is affected by spatial and temporal variations of environmental parameters, potentially can be used as a means for remote sensing of the changing arctic ocean and monitoring the water/ice/snow/air system at ranges up to a few tens of kilometers. Recently developed technology, methods, and systems allowed dependable measurements of sound transmission under ice at such ranges. Here we consider results of data analysis for two recent experiments on midfrequency transmission under ice in the Beaufort Sea, APL-ICEX14 [1] and NPS-ICEX16 [2].

The ICEX14 measurements were made for fixed geometry with source and receiver having same ~30m depth at ~720m distance from each other, and acoustic intensity timeseries was recorded from transmission of five 3500Hz 5s-long CW pulses (one per minute). A detailed description of the ICEX14 experiment, environmental conditions in the area, a hybrid approach that combines PE, Image Source, and Ray models, developed for the data analysis, and results of model-data comparisons, are given in a just published JASA

paper [3], attached. In this report, a brief description of the approach and some results are given for completeness.

The second dataset, NPS-ICEX16 [2], is much bigger, and this report presents results of its trial/preliminary analysis based on using the same (in general) hybrid approach [3], which was adjusted for the used waveforms, ranges, and depths. The NPS-ICEX16 experiment used five spatially separated fixed hydrophones and two mobile sources, EMATT1 and EMATT2, that provided five 10-hours-long timeseries of acoustic pressure at different combinations of source-receiver ranges (0.3-10km) and depths (45-183m). Waveforms transmitted by EMATT2 were sequences of 57s-long CW pulses at 2800Hz and 2300-3000Hz 3s-long LFM sweeps (EMATT2), while EMATT1 was concurrently transmitted only 57s-long CW pulses at 950Hz.

For analysis of data from both experiments, a hybrid modeling approach was developed [3-5], that considers several types of arrivals contributing to the received signal under ice at different time intervals. The direct arrivals resulting from nearly horizontal propagation under ice at short and medium ranges are described using a presentation of the full-wave field of a point source in a stratified ocean as a sum of two components. For the first one, a fast PE code is employed assuming a flat ice-free surface to account for effects of structure and dynamics of the arctic surface duct. The second component is the field of an image source whose strength is defined by a reflection loss factor, $1 + V(\theta)$, given for the ice cover by its complex reflection coefficient V at grazing angles θ defined for ray paths between the source and the ice-water interface. Also, it is assumed that bottom reflections can be neglected either due to the upward refraction or by windowing-out the later (bottom-bounced) arrivals.

This approach is applicable to various models of plane-layered ice, e.g., elastic or poro-elastic, given a specific form of $V(\theta)$. For the coherent part of the field, effects of ice roughness can be included as well by introducing a coherence-loss factor, so that

$V_{rough} = V \exp\left(-\frac{P^2}{2}\right)$ where $P = 2k\sigma \sin(\theta)$ is the Rayleigh parameter, k is the wave number in water, and σ is the rms roughness. For high enough frequencies or very rough ice (where $k\sigma \gg 1$) this means that coherent reflections can be ignored unless the grazing angles are small enough and $\sin(\theta) < 1/(k\sigma) \ll 1$. If, at these frequencies and angles, both compressional and shear penetrations are smaller than the ice layer thickness, the layering effects on the coherent field under elastic ice cover can be ignored as well. Otherwise, the coherence-loss correction may be more complicated [6].

As a numerical example, at 3.5 kHz, for ICEX14 environment (given the sound speed profile and ~2m-thick ice cover) and geometry assuming $\theta = 5^\circ$ (corresponding to ice reflections at ~720m source-receiver range), one obtains the complex strength of the image source $1 + V = 0.2 + 0.4i$ for flat ice ($\sigma = 0$), and $1 + V_{rough} = 0.6 + 0.2i$ for very rough ice ($\sigma = 0.5$ m), the needed input values for coherent TL calculations in the vicinity of the receiver location, which are shown in Fig.1 [3]. An unexpected finding at this stage is that presence of ice cover results in a greater sensitivity to the range, which made it possible to explain observed ~2dB changes of TL within five minutes of the ICEX14 experiment by environmental dynamics causing variations of range for a few meters between pings (one per minute).

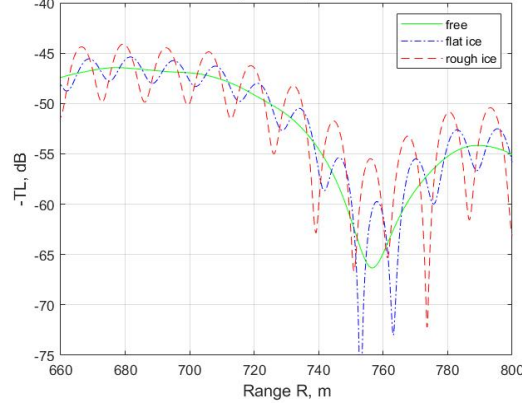


FIG. 1. ICEX14 range-dependences of $-TL$ derived using a hybrid PE-ImageSource-Ray approach that accounts for presence of elastic ice cover, either flat or rough, and allows comparisons to the ice-free case [3].

The next stage is calculating the reverberation coda that follows the above-described direct signal. The coda is modeled by bottom- and ice-bounced arrivals from steeper angles, where the coherent component of reverberation caused by specular reflections from ice and bottom may be reduced due to their roughness, and the effects of refraction on propagation in the water column are of lesser significance as well. The incoherent component of reverberation can be modeled in terms of the ice and bottom scattering strengths as functions of incidence and scattering grazing angles. For the bottom, an appropriate model is available [7]. What is not available yet is a physics-based model of midfrequency scattering from ice cover, whose complexity requires concurrently including effects of its roughness, volume heterogeneity, elasticity, and layering. At this existing background stage of development, for the sake of a simplified parameterization of scattering data, empirical Lambert-like expressions are used, which in a quasi-monostatic case are of the form

$$m_s(\theta) = M_0 * (\sin \theta)^\gamma. \quad (1)$$

Such a semi-empirical approach was used recently in the ICEX14 data analysis [3,4]. Results of model-data comparison are shown in Fig.2 for the average intensity timeseries including both the direct arrival and reverberation coda, with model input parameters given in Table 1.

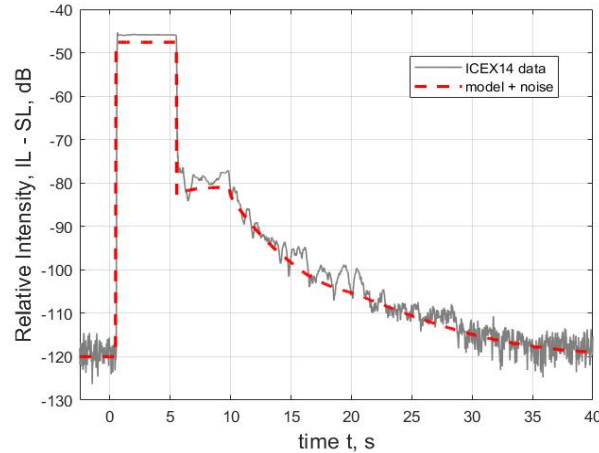


FIG.2. The acoustic intensity time series comparison between measured ICEX14 data and model results [3].

TABLE 1. Parameters used in the models of ice cover and bottom [3]

Model parameters	Ice	Bottom
Density, g/cm ³	0.9	2.7
Compressional Wave Speed, m/s	3800/(1+0.01i)	4800/(1+0.01i)
Shear Wave Speed, m/s	1600/(1+0.03i)	2000/(1+0.03i)
Thickness, m	2.0	∞
RMS roughness, cm	0 & 50	0 & 5
Backscattering strength at nadir, Mo	0.015	0.01
Power exponent, γ	2.0	2.5

Consider now some results of the ICEX16-NPS experiment [2,5] which used mobile sources EMATTs. In Fig.3 are two examples of measured transmission loss (red dots), normalized (to source level) intensity range series at different frequencies and source/receiver depths; (a): 950 Hz, source/receiver depth both are 183m; (b): 2800 Hz, source/receiver depth both are 46m. The data is compared to Bellhop (ray-based) model results (shown by black curves) assuming an ice-free surface.

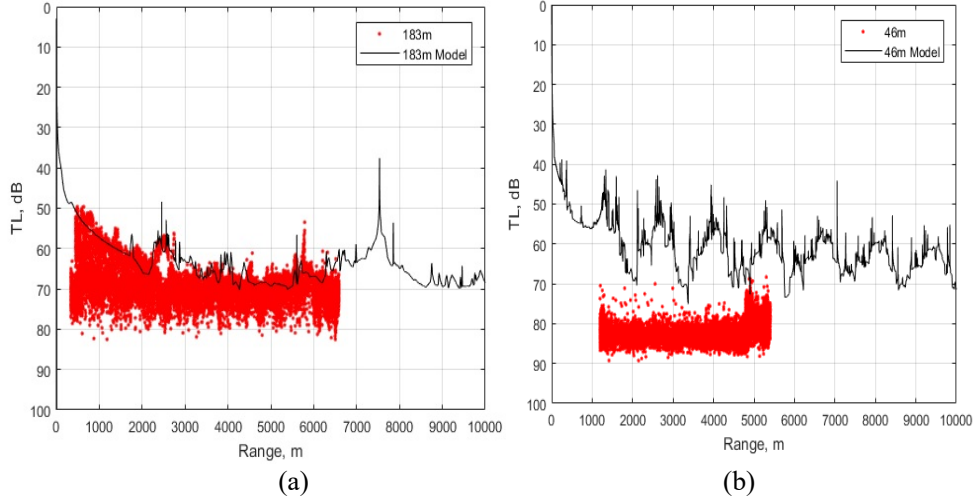


FIG.3: ICEX16 NPS-measured CW transmission loss (red dots) as a function of range at different frequencies and source/receiver depths, (a): 950Hz and 183m, (b): 2800Hz and 45m. Bellhop model results (black curves) assume ice-free surface. The examples are taken from [2], Fig.21(b) and Fig. 26(c).

To account for presence of ice cover, the same combined PE / Image source/ Ray approach to coherent TL at short and medium ranges was used [5], and results are illustrated in Fig.4. The bounds of modeled TL are roughly the same as the measured TL data spread shown in Fig.3(a). Note that the Bellhop model for the ice-free case, in this example, is able to outline only a higher bound of data but fail to predict strong variations of TL. Data shown in Fig.3(b) is yet to be properly modeled and better understood.

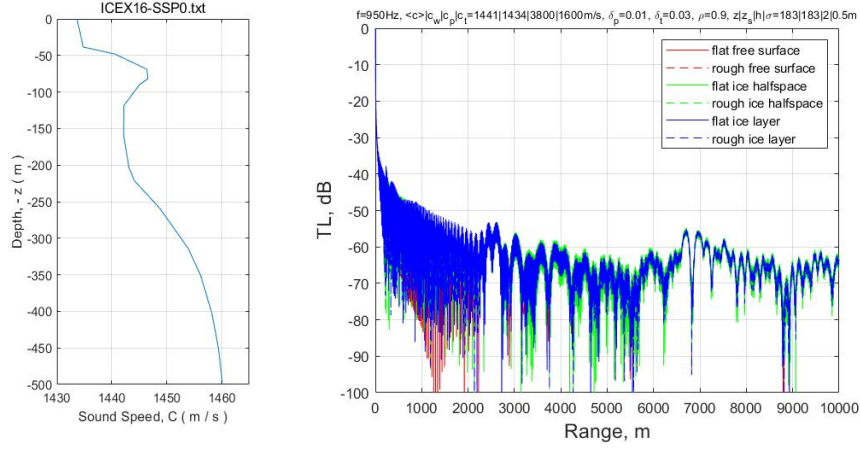


FIG.4. ICEX16 sound speed profile (left) and Transmission Loss at 950 Hz as a function of range (colored curves) calculated using a combined PE / Image source/ Ray approach for ice-free and ice-covered ocean, either flat or rough [5]. Ice parameters are in Table 1.

In addition to estimating TL, processing of spectrograms for ICEX16-LFM sweeps allows inferring the scattering strength, a major acoustic characteristic of ice, at different frequencies and angles. An example at 2950 Hz is shown in Fig.5, which assumes the Lambert parameterization (1) and gives estimates for empirical parameters M_0 and γ .

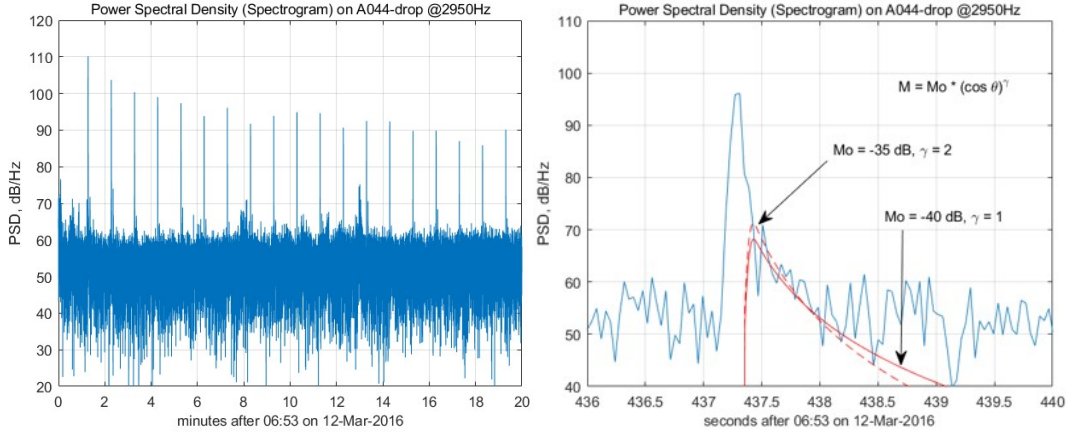


FIG.5. A 2950Hz spectrogram of ICEX16 pressure time series at a fixed 125m-depth receiver from moving at 183m-depth EMATT2, for first 20 minutes (left), and zoomed-in to isolate an LFM sweep and coda at the 7th minute (right), with inferred angular dependence of the ice scattering strength (red curves) [5].

The next step in developing remote sensing techniques could be based on exploiting relationships between the scattering strength and physical properties of sea ice. However, such relationships have not yet been adequately understood, and a geo-acoustic ice interaction model (GAIM) that accounts for midfrequency effects of layered structure combined with ice elasticity, roughness, and heterogeneity, has not yet been developed.

There is a deceptively similar model which was developed for analysis of midfrequency ocean bottom reverberation, Geo-Acoustic Bottom Interaction Model (GABIM). However, it considers elasticity only for bottom basement half-space but does not include the case of

rough elastic layers. GABIM input parameters do not include the elastic layer thickness, which is critical for acoustic sea ice interaction. Thus, GABIM is inapplicable to arctic ice at mid and low frequencies where penetration depths for both compressional and shear waves may be comparable with the ice thickness, and ice cover boundaries (such as ice/snow/air interfaces) cannot be ignored. A discussion of these issues in [7] gives a conclusion as follows: “Finally, a very significant improvement to GABIM will be possible once the problems of roughness and volume scattering in layered elastic media are solved”.

Therefore, there is a noticeable gap in modeling, and this gap significantly limits further development of remote sensing techniques for monitoring the sea ice state and inferring critical ice properties from under-ice acoustic measurements.

This trial project develops a base for future work aimed to resolve the problem. It can be focused on developing a physics-based (geo-acoustic) model for incoherent scattering from the sea ice that provides relationships between ice properties and transmission intensity time series (via two major measurable characteristics, reflection loss, RL, and bistatic scattering strength, BSS). It can be called Geoacoustic Ice Interaction Model, GAIM, since it stems from a similar motivation for developing GABIM (~10years-long effort prior the 2010 publication, [7] and Refs therein). However, the difference from GABIM is significant, as GABIM allows only the case of elastic half-space, and shear waves are ignored in the sediment layers, i.e., the model does not include the elastic layer thickness, a critical ice parameter at mid and low frequencies.

The model (GAIM) for scattering from rough heterogeneous elastic layered media can exploit a general formalism previously used for seafloors [7-10] but will need modifications to be applicable to the sea ice as well. The main modification, which is required specifically at mid frequencies, is including shear as a scattering mechanism of the layer adjacent to water (the elastic ice layer of finite thickness). The new model is to provide relationships of coherent reflection coefficient and incoherent scattering strengths of the ice with its parameters, such as the layer thickness, density, compressional and shear speed and attenuation, spatial spectra of roughness and heterogeneity.

RELATED PROJECTS

This research was built on results of previous and current projects on propagation, reverberation and scattering in heterogeneous marine environments funded by ONR-OA and assumed collaboration with Dr. Kevin Williams at APL-UW and other investigators working in this field. This work leverages results of most recent research funded by ONR-OA [1,3-5], as well as Ivakin’s previously ONR-funded research on scattering and reverberation in complex environments [7-16]. The ICEX16 data analysis assumes an ongoing [5,17] collaboration with Drs. John Joseph and Ben Reeder of Naval Postgraduate School.

IMPACT/APPLICATIONS

This work assumes resulted in practical suggestions for analysis of NPS EMATT data base and planning some specifics of future EMATT experiments [5,19]. This research is to contribute to further development of a general tool for analysis of propagation, scattering, and reverberation in the complicated Arctic Ocean environments.

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- ❖ Anatoliy N. Ivakin and Kevin L. Williams, “Midfrequency acoustic propagation and reverberation in a deep ice-covered Arctic ocean”, *J. Acoust. Soc. Amer.*, **152**(2), 1035-1044; published online 18 August 2022, <https://doi.org/10.1121/10.0013503>.
- ❖ Anatoliy N. Ivakin, John E. Joseph, and D. Benjamin Reeder, “Midfrequency sound transmission from mobile sources in a deep Arctic ocean at short and medium ranges: Time-domain modeling and data analysis”, *J. Acoust. Soc. Am.*, **151**, A190 (2022).
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Midfrequency acoustic propagation and reverberation in a deep ice-covered Arctic ocean

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ABSTRACT:

A model-based analysis of sound transmission in a deep ice-covered Arctic ocean recorded during the Ice Experiment 2014 is presented. A source of opportunity transmitted mid-frequency (3500 Hz) 5 s duration continuous wave pulses. The source and receiver were omnidirectional, located under ice at a ~ 30 m depth at a ~ 719 m distance from each other. Recorded acoustic intensity time series showed a clear direct blast signal followed by an about 30 s duration reverberation coda. The model considers several types of arrivals contributing to the received signal at different time intervals. The direct signal, corresponding to a short-range nearly horizontal propagation, is strongly affected by the presence of a weak near-surface (within 50 m depth) acoustic channel. Reverberation coda that follows the direct signal corresponds to medium-range bottom- and ice-bounced arrivals from steep angles which are controlled by reflectivity and scattering strengths of ice and bottom, their physical properties, and acoustical parameters. © 2022 Acoustical Society of America. <https://doi.org/10.1121/10.0013503>

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I. INTRODUCTION

Most acoustic experiments in the Arctic are aimed at better understanding the sound interaction with a complicated ice-covered dynamic ocean environment and, based on this understanding, finding a way to remotely assess and monitor the environment at different spatial and temporal scales. In many cases, the emphasis is on low-frequency long-range propagation and large-scale observations (up to across the Arctic Ocean scales); see, e.g., overviews by [Howe et al. \(2019\)](#) and [Worcester et al. \(2020\)](#). Also, in many cases, the presence of ice cover, fine structure of a relatively thin surface duct (within 45–60 m depths), may not be critical as only acoustic paths which are below this duct survive over the large ranges of interest. The same reason allows neglecting paths with multiple bottom interactions. At higher frequencies and shorter ranges, however, the related effects become more important and directly observable; see, e.g., [Yang and Hayward \(1993\)](#) and [Jensen et al. \(2011\)](#). Such observations may be a valuable source of information, although at smaller spatial scales, about ice cover state and characteristics, bottom parameters, and under ice water properties and dynamics.

This paper presents results of midfrequency acoustic observations for transmission of 3.5 kHz, 5 s pulses in a deep ice-covered Arctic ocean made during the Ice Experiment 2014 (ICEX14). Details of the experiment and environmental conditions are described in [Williams et al. \(2018\)](#) and [Ivakin and Williams \(2020\)](#). Recorded acoustic intensity time series showed a clear direct blast signal followed by an about 30 s duration reverberation coda.

The main goal of this study is to provide a model-based analysis for each segment of the measured time series, suggest their physical explanation in terms of specific sound propagation and scattering mechanisms, and particularly quantify roles of the Arctic near-surface duct, ocean bottom, and ice cover.

The paper is organized as follows: in Sec. II, the ICEX14 data on acoustic propagation and reverberation are described. In Sec. III, a direct blast signal is considered using combined ray-based and full-field (PE) models for under-ice propagation. In Sec. IV, a model for the reverberation coda is presented, and results of model-data comparison are discussed. Summary and concluding remarks are given in Sec. V.

II. ICEX14 DATASET

The dataset on acoustic propagation and reverberation discussed in this paper was obtained in an ice-covered region of the Beaufort Sea in March 2014 during one of the ICEX14 experiments. Water depth was greater than 3.5 km and the ice in the area was ~ 2 m thick. A typical depth-dependence of sound speed measured in the ICEX14 area is shown in Fig. 1 and is used in this paper as a representative example, as no such profiles are available for the specific location and time of acoustic measurements of opportunity (discussed here) during their short (about 5 min) duration.

Midfrequency transmissions from an omnidirectional source of opportunity located under ice at a ~ 30 m depth were recorded on a hydrophone located at the same depth at a ~ 719 m range from the source. The acoustic measurements discussed here were performed within a short, 5 min time span during which five consecutive 5 s duration CW pulses at 3.5 kHz were transmitted, one per minute. Figures

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2(a) and 2(b) show time series of a relative intensity (RI), that represents recorded acoustic intensity level (IL), squared magnitude of received pressure envelope (in dB units), relative to source level (SL). Note that it has the same magnitude as, but opposite sign as, transmission loss (TL), i.e., $RI = -TL = IL - SL$. All five received time series, aligned relative to each ping's start time, are shown by solid lines, and the average over the five pings is shown by a thick dashed line.

A distinctly different behavior of the data are seen in two different time intervals. The short times (~ 0.5 – 5.5 s) correspond to direct arrival of the 5 s duration pulses transmitted from the rather short direct-path distance (~ 719 m). The time series zoomed in and shown in Fig. 2(b) for detail, vary approximately 0.9 dB around the average value, which gives an estimate for the transmission loss of the direct arrivals, $TL \approx 45.9 \pm 0.9$ dB. The direct arrival signal and following reverberation coda [Fig. 2(a)] are above noise level (~ -120 dB, seen as a background) within a time interval $t \sim 0.5$ – 35 s, which is associated with short-to-medium ranges, $ct \sim 0.75$ – 50 km. Here, c is the sound speed in the water and t is the propagation time counted from beginning of each ping.

The second time interval includes reverberation signal associated with possible bottom bounces. The signal starts at time ~ 5 s that corresponds to ~ 7 km range (approximately two bottom depths), although it can be seen only after ~ 5.7 s because its beginning (at ~ 5 – 5.7 s) is well below the level of direct blast signal. If just a little shorter transmitted pulse was used, e.g., 3 s instead of 5 s duration, the direct arrival would have a much clearer separation from the coda. The shape of the coda shows a somewhat different behavior in the first part ($t < 10$ s) where it has a plateau at ~ -80 dB level, then a sharp back edge at $t \sim 10$ s, and following decay to a noise level at $t > 35$ s.

Note that the source and receiver clocks were not synchronized, so the estimates of arrival time for the beginning of direct blast signal relative to the ping start time seen in

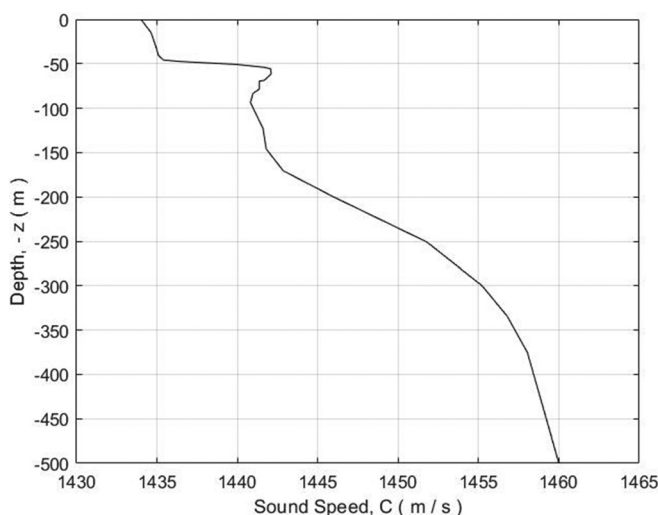


FIG. 1. A typical sound speed depth-profile measured during the ICEX14.

Fig. 2(b) (~ 0.7 s) and related parameters assume a typical value for sound speed in the water under ice at the source–receiver depth (30 m), $c_0 = 1435$ m/s (see Fig. 1). For some other important estimates, however, only relative times are needed. For instance, the time difference between back edges of the direct arrival and the first part of the coda (clearly seen in Fig. 2 at 5.5 and 10 s, respectively) provides a simple estimate for a specific ocean depth under the drifting ice during the 5 min duration acoustic experiment, ~ 3700 m, which will be used later in analysis of the coda.

III. DIRECT ARRIVALS: SHORT-RANGE PROPAGATION IN A SURFACE DUCT

A. Approach

In this section, the short-time interval of the received signal (at ~ 0.5 – 5.5 s) corresponding to direct arrivals is considered in more detail and analyzed. Numerical simulations of under-ice propagation in the surface duct can be made using elastic full-wave codes, see, e.g., Jensen *et al.* (2011), and Frank and Ivakin (2018a,b). Although such calculations are time consuming, they could be worthwhile in the case where the sound speed profile (SSP) and source location are known with sufficient accuracy. As it is not the case in our experiment, for simplicity and faster calculations, we use a Range-dependent Acoustic Model (RAM) based on Parabolic Equation (PE) initially developed for fluid ocean environments with free flat surface (Collins, 1999), for brevity called here standard PE, which is slightly modified here to take into account effects of elastic ice cover, either flat or rough, using some simple ray-based considerations. The goal is to understand and quantify mechanisms affecting the measured intensity level and its variation over time of observations (~ 5 min).

The SSP (see Fig. 1) clearly shows presence of a near-surface duct (~ 45 m thick) above a gradient/transition layer (~ 45 – 55 m). Although this profile is just a representative example, the surface duct is a typical feature of this ice-covered environment, so we will start from this SSP, which defines a set of environmental inputs to an initial scenario (scenario 1, free flat surface, and standard PE model is used). Other inputs are defined by the source and receiver locations, their depths, and range (horizontal separation). Then, we consider other scenarios to assess the effects of possible corrections, variations, and uncertainties in the range- and depth-dependences of the acoustic intensity caused by relatively small changes of SSP. Finally, effects of ice cover will be shown using some ray-based corrections to standard PE solutions. For all the scenarios, a connection between the simulated range–depth dependencies with observed acoustic intensity time series will be discussed in Secs. III B, III C, and III D.

B. Effects of SSP variations

First, starting with scenario 1, we want to demonstrate that, while the surface waveguide is relatively weak (with only ~ 7 m/s for total variations of the sound speed), it

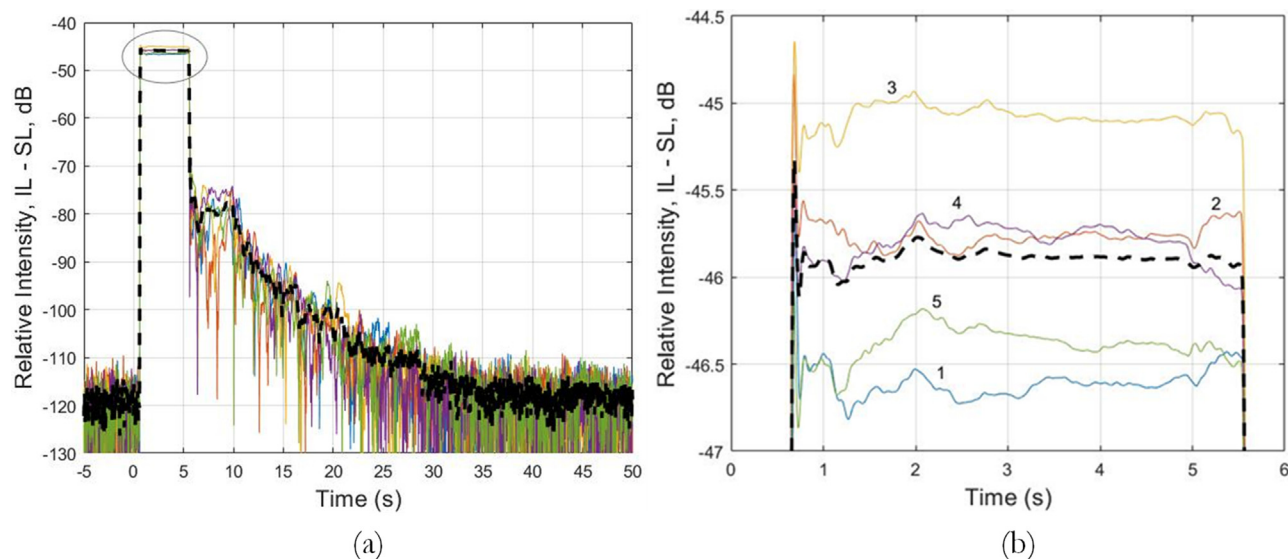


FIG. 2. (Color online) Relative Intensity timeseries (solid lines) and their average (dashed) for all five transmitted pings (1–5). The entire time series are shown with an ellipse that surrounds direct arrivals (a), which are zoomed in for more detail (b).

happened to be sufficient, for this specific experiment geometry, ranges, and depths, to cause a noticeable enhancement of intensity due to a focusing effect of refraction within the gradient layer that appears, in ray-based terminology, as a caustic near the receiver location (Brekhovskikh and Lysanov, 2003).

Using a standard PE solution for scenario 1 (SSP given in Fig. 1 with free ocean surface) results in Fig. 3 which shows range–depth contours for relative intensity ($-TL$) and clearly confirms that the receiver is located in the area of enhanced intensity.

For the sake of faster computer simulations, now we assume that, at short times considered here, deep ocean layers have little effect on propagation, and can be ignored, i.e., they will be truncated and replaced by a non-reflecting absorbing bottom that plays here a role of a perfectly matched layer (PML). Note that the initial profile (SSP1) is truncated at the deepest point of available SSP data (500 m), which significantly increases the calculation time, even using a rather fast standard PE model. Examining SSP variations would require multiple calculations and a much larger volume of simulations and associated computer time. To reduce those, the SSP can be truncated “properly,” i.e., without any significant effect on model-data comparisons.

For an illustration, consider two more profiles, 2 and 3, shown in Fig. 4(a), both being significantly different from SSP1 and from each other, and compare the results of simulations for the three profiles, which are presented in Fig. 4(b), for the range- and depth-dependences of acoustic intensity. It is clearly seen that effects of stratification in water columns deeper than ~ 60 m are rather small for most of the depths and ranges. There are some locations though with noticeable sensitivity caused by wave interference due to multipaths (using ray terms). At those locations, amplitudes of different rays are comparable that results in more pronounced minima and maxima of interferential patterns.

SSP3 is chosen as a “properly” truncated sound speed profile for further comparisons to show critical importance of SSP variations within the surface channel. The standard PE model with ice-free flat ocean surface is used for simulations and results of comparisons for SSP 3–5 shown in Fig. 5(a) are presented in Fig. 5(b) again for range- and depth-dependencies of acoustic intensity. It is seen that even small SSP variations in the surface duct and its lower boundary, the gradient layer, may result in very large (tens of dB) variations of transmission loss at the receiver.

C. Effects of elastic rough ice cover

For further analysis, we choose scenario 4 as it gives results for the predicted transmission loss close to that observed in our experiments. Our goal now is to suggest a way to correct the results for presence of ice cover. To make these corrections, we use a ray-based approach combined with the method of images and consider an additional acoustic field from an imaginary source assuming that its amplitude is taken such that it will (1) compensate the reflection from the free surface, and (2) add the reflection field corresponding

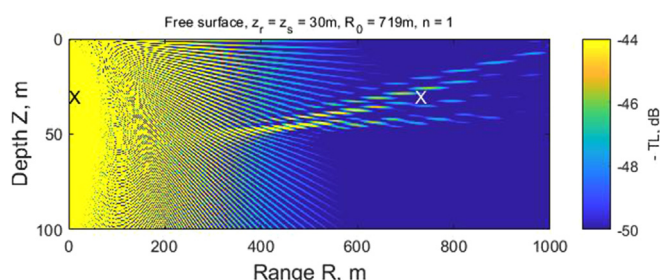


FIG. 3. (Color online) A range–depth image of Relative Intensity in dB units, $-TL$. It resulted from PE-based calculations assuming free ocean surface and sound speed depth-profile shown in Fig. 1. Locations of source and receiver are shown by crosses. Note an enhancement of intensity near the receiver location caused by focusing effects of refraction in the surface duct.

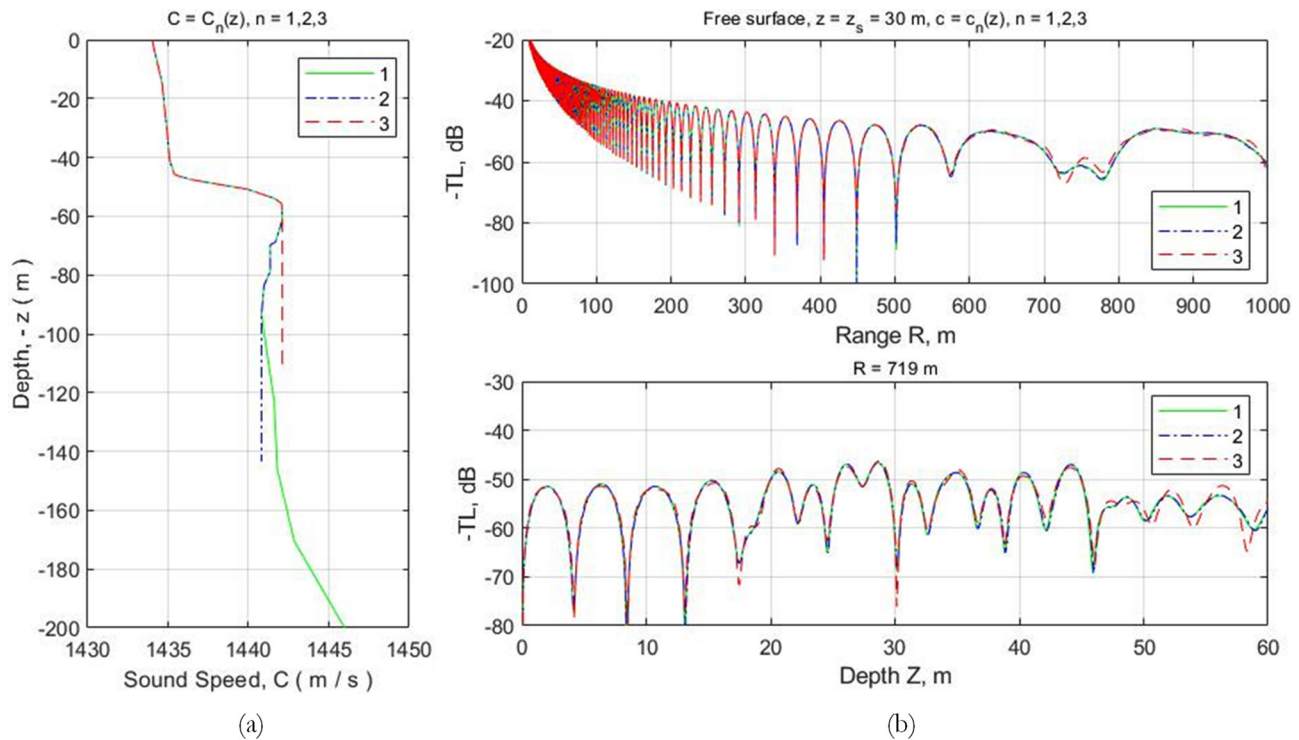


FIG. 4. (Color online) Sound speed profiles (SSP 1–3) which differ only at depths below the surface duct (a), and corresponding range- and depth-dependences of Relative Intensity in dB units, $-TL$ (b). Free of ice ocean surface is assumed.

to the real surface, the ice cover. It is easy to show that, in case of a homogeneous water layer under the ice, such source amplitude is $1+V$, where V is the complex reflection coefficient of the ice layer. In the case of a slightly stratified water under ice, it would have a simple additional phase-correction factor for the imaginary source amplitude. In our case of a very slight stratification at 0–40 m depths, as in scenario 3 [Fig. 5(a)], this factor is not critical and can be omitted.

Consider now the reflection coefficient from an elastic ice cover. Figure 6 shows its real and imaginary parts as functions of incidence angle for several cases. Two curves on each subplot show results for two cases of flat ice; one is for 2 m ice layer thickness, and another is for a half-space. Ice parameters (see Table I) are representative but typical for use in various elastic models and computer simulations (see, e.g., McCammon and McDaniel, 1985; Williams and Francois, 1992). Important is that at near-grazing incidence, in the 70° – 90° interval, the results in both cases are coincident and correspond to the limit case of the infinite layer thickness, or half-space. This is because, at these angles, both compressional and shear waves in ice are evanescent and their penetration to ice is smaller than the ice layer thickness. At the ranges of interest here, ~ 720 m, all possible incidence angles are well within the mentioned interval of near-grazing incidence angles. For source and receiver depths ~ 30 m, the specular reflection (incidence) angle θ is $\sim 85^\circ$, and, according to Fig. 6, one obtains $W = 1 + V \sim 0.2 + 0.4i$, the needed input value for flat ice.

Two more curves on each of subplots in Fig. 6 show results corrected for the ice roughness using corresponding coherence-loss factors in reflection coefficients, $V_{rough} = V_{flat} \exp(-P^2/2)$,

where $P = 2k\sigma \cos(\theta)$ is the Rayleigh parameter, k is wave number in water, and σ is the ice RMS (root-mean-square) roughness. Two values for the roughness parameter are taken, $\sigma = 0.2$ m (moderately rough ice) and $\sigma = 0.5$ m (very rough ice). At $\theta = 85^\circ$, in the case of a very rough ice, one obtains $W = 1 + V_{rough} \sim 0.6 + 0.2i$, another needed input value to show the effect of ice roughness. Results comparing the cases of free surface, flat ice, and very rough ice, are shown in Fig. 7, for depth- and range-dependences of transmission loss in the vicinity of the receiver location.

The curves for the relative intensity level ($-TL$) as function of range and depth shown in Fig. 7, as expected, are oscillating and give TL values very sensitive to the receiver location (and the source location as well, due to the reciprocity principle).

D. Discussion

An important new feature is that presence of ice cover, either flat or rough, results in additional range dependent oscillations [O(10m)] of TL, which are much smaller than those in the free surface case, and which also may significantly increase the slope of the TL curve up to ~ 1 dB/meter. Assume, for instance, that source–receiver exact locations allow some dynamical changes around nominal range, say $\pm$ a few meters horizontally, which for the source of opportunity and an ice-tethered receiver in this experiment is a reasonable estimate, considering possible relative ice–water movement caused, e.g., by currents and winds (Williams *et al.*, 2018). Then, using the variations seen in Fig. 7(b) at 719 m over a few meters, scenarios with ice cover, both flat

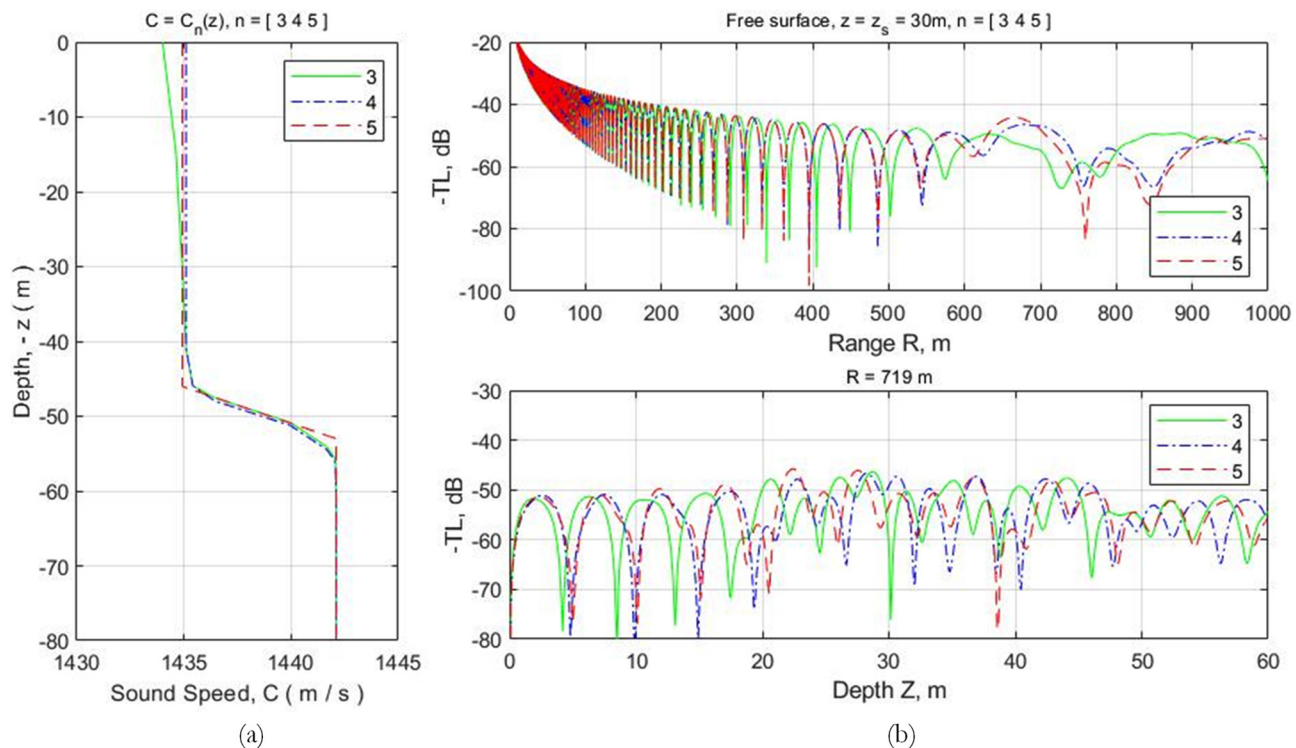


FIG. 5. (Color online) Sound speed profiles (a) which differ only within the surface duct (unlike those shown in Fig. 4), and corresponding range- and depth-dependences of Relative Intensity in dB units, $-TL$ (b). Free of ice ocean surface is assumed.

and rough, one obtains approximate bounds for transmission loss, $-TL \approx -48 \pm 2$ dB.

Although this estimate is within a reasonably good fit to rough bounds of measured transmission loss, $-TL \approx -46 \pm 1$ dB [see Fig. 2(a)], the difference (~ 2 dB) can still be informative. For instance, Fig. 7(a) shows a significant sensitivity to rather small vertical variations of source and receiver locations. Changing either source or receiver depth

from 30 to 28 m, according to Fig. 7(a), would enhance the acoustic intensity to the observed values.

Another practical way to use this difference between observed and predicted transmission loss may be adjusting the gradient layer depth and/or its shape for which the slight evolution within the time of acoustic observations (here, the 5 min time span that includes all the five pings) may be a reasonable assumption. Assume, for instance, that the

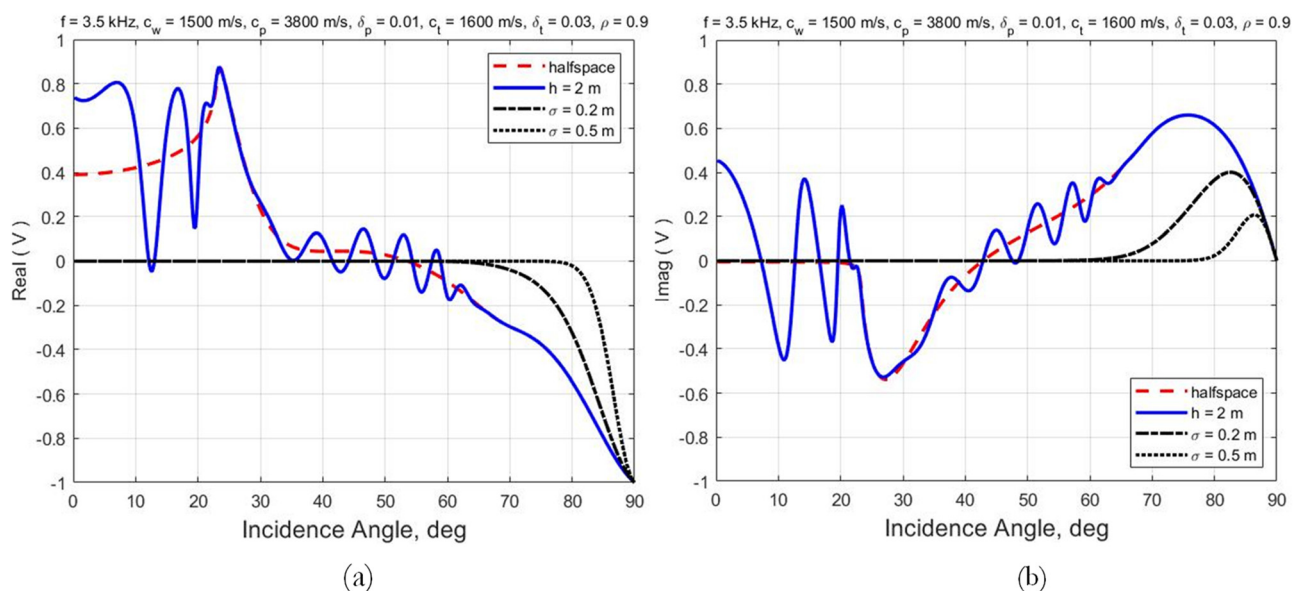


FIG. 6. (Color online) Real (a) and imaginary (b) parts of the reflection coefficient from an ice cover represented by either flat or rough elastic half-space and 2 m-thick layer.

TABLE I. Parameters used in the models of ice cover and bottom.

Model parameters	Ice	Bottom
Density, g/cm ³	0.9	2.7
Compressional wave speed, m/s	3800/(1 + 0.01i)	4800/(1 + 0.01i)
Shear wave speed, m/s	1600/(1 + 0.03i)	2000/(1 + 0.03i)
Thickness, m	2.0	∞
RMS roughness, cm	0/20/50	0/3.5/5
Backscattering strength at nadir, M	0.015	0.01
Power exponent, γ	2.0	2.5

gradient layer slightly changes its depth, say, for a few tens of centimeters from its typical depth (~ 50 m) over a few minutes, which can be caused, for instance, by internal waves. Then, according to Fig. 5, corresponding variations of acoustic intensity at the receiver could be on the order or greater than observed.

Both types of dynamics, horizontal changes in source-to-receiver distance, and vertical changes in the gradient layer depth, can be important as a potential tool for monitoring ocean water dynamics, which can be caused, for instance, by local currents, internal waves, or other mechanisms of SSP evolution. Recently, a somewhat similar approach based on measuring reflection from a gradient layer in the water column was used at much lower frequencies using seismo-acoustic instruments to observe dynamics of the varying gradient layer parameters, depth, and structure (Zou and Zhang, 2021).

Note, however, that such monitoring would require a sufficiently high stability of transmitted sound level and well controlled source–receiver locations. Here, to the authors’ knowledge, the stability of the source location and sound level were high enough to somewhat narrow down the number of possible mechanisms and to believe that

observed temporal variations of the received intensity and transmission loss [Fig. 2(b)] can be explained by either some variations in the receiver location (around the nominal location, here 30 m depth and 719 m range) or slight evolution of the sound speed profile during the experiment (within ~ 5 min time span). Both can be caused by hydrodynamic processes, for instance, internal wave or currents/winds driven relative ice-water movement, which can change the range between source and receiver over the timescale ~ 1 min between the pings.

For more insight into effects of the surface duct, and particularly the role of transition layer and its focusing effects, consider a ray model for a simple profile shown in Fig. 5(a) (profile 5), which corresponds to a linear gradient layer between two homogeneous half-spaces, $z < z_1$ and $z > z_2$, with sound speeds c_1 and c_2 , respectively, assuming that the source and receiver are located above the gradient layer at depths z_S and z_R . In this case, the intensity of the refracted path is increased by a focusing effect of the gradient layer, and for the focusing factor’s range–depth dependence one obtains $F(r, z) = 1/\sqrt{1 - q}$, where $q(r, z) = 2H(z)/(ar^2)$, $H = |z_1 + z_2 - z_S - z|$, and $a = (1/c_1)dc/dz = |c_2 - c_1|/(c_1|z_2 - z_1|)$. The focusing factor is constant in the range–depth space along the curves where $q(r, z)$ is fixed, with $q(r, z) = 1$ being equation of the caustic. This also explains connection between effects of changes in the thickness and location of gradient layer, and source–receiver geometry. For illustration, consider a numerical example. Given the fixed source–receiver depths and range ($z_R = z_S = 30$ m, $r = 719$ m), the relative change of sound speed over the gradient layer (its “strength”) and its location ($|c_2 - c_1|/c_1 = 0.005$, $z_1 = 47$ m), one finds that caustic will appear near the receiver location if the gradient layer thickness increases from ~ 7 to ~ 20 m.

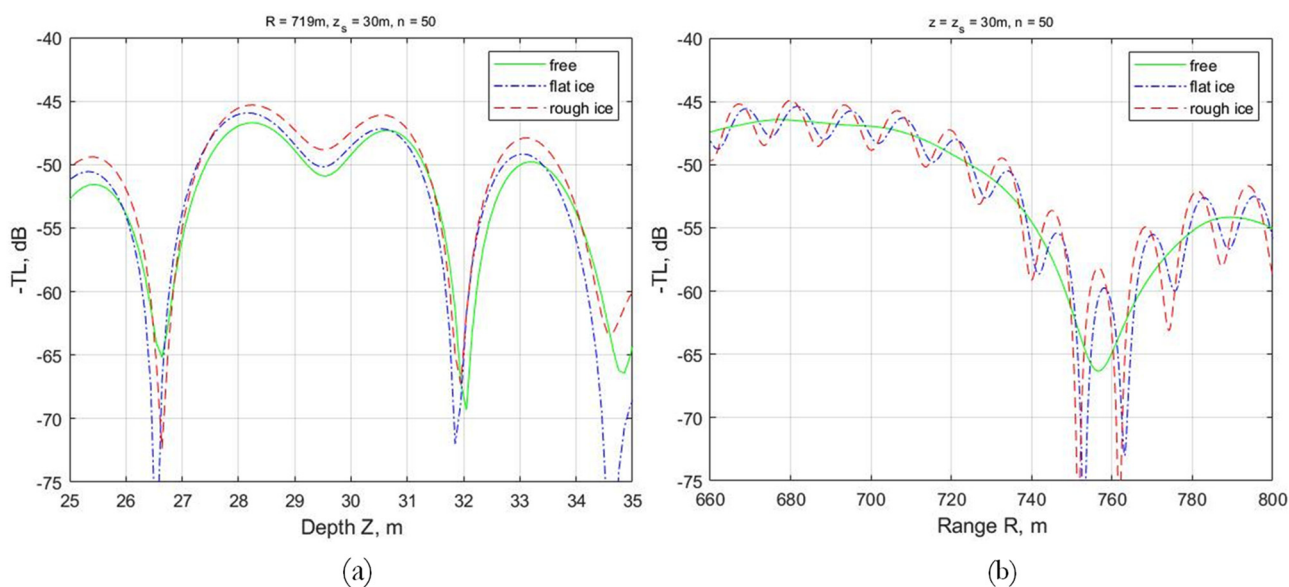


FIG. 7. (Color online) Depth- (a) and (b) range-dependences of $-TL$ derived using combined PE–ray-based approach that accounts for presence of elastic ice cover, either flat or rough, and allows comparisons to the ice-free case. Results are presented for SSP4 shown in Fig. 5(a) and zoomed in for more detail in the vicinity of the receiver location.

IV. MEDIUM-RANGE REVERBERATION CODA

A. Approach

Note that the combined ray-PE model, used here to describe the direct arrival, is a small-angle approximation of the full-wave solution, i.e., it includes only possible nearly horizontal short-range paths with ice reflections and in-water refractions, but excludes nearly vertical bottom and ice reflections which arrive later along medium-range paths as a part of reverberation coda. These steep-angle paths are practically not affected by water stratification, and associated arrivals' intensities can be estimated following, in general, an approach used in [Ainslie *et al.* \(2016\)](#) and a semi-coherent multiple specular reflections (MSR) model described therein. However, some modifications are needed to adjust this model to a medium-range ice-covered deep-ocean reverberation scenario the typical details of which are described, e.g., in [Yang and Hayward \(1993\)](#) and [Jensen *et al.* \(2011\)](#).

One such modification is that now the model replaces a free water surface by an ice cover whose effect is accounted in terms of an angular dependence of coherent reflection coefficient (see Fig. 6). Correspondingly, the propagation loss factors are corrected to account for additional loss due to reflections from ice. A second modification exploits conditions, rather common for deep water scenarios where source and receiver depths are much smaller than the ocean depth, which allows a simplified treatment of the so-called "4-paths semi-coherent effect." In general, this is similar to an effective directivity pattern effect discussed in [Jensen *et al.* \(2011\)](#). In the case of ice cover, combined source and receiver Lloyd-mirror-like patterns form an "effective directivity" defined in terms of reflection coefficients of ice at outgoing (from the source) and arriving (to the receiver) angles from nadir. Then the "4-paths effect" is automatically included for all propagation paths between ice and bottom. However, this effect can be significantly reduced in the case of rough ice because of the coherence-loss correction factor, as was discussed earlier in Sec. III C. This means that in the case of rough ice, at these steep angles, the paths that include ice reflections can be neglected.

Note also that the approach used in [Ainslie *et al.* \(2016\)](#) originally assumes monostatic scenarios with no horizontal offset of the receiver from the source. In our experiment, the source–receiver separation in the horizontal plane is considerable. Strictly speaking, a bistatic scenario should be considered, see, e.g., [Ellis and Crowe \(1991\)](#) and [Williams and Jackson \(1998\)](#). It is known, however, that bistatic effects in reverberation are negligible at large enough times much greater than the time of direct propagation between source and receiver; see, e.g., [Urlick \(1960, 1970\)](#). This is the case for the geometry of our midrange reverberation measurements where ranges are large (~ 7 km and larger) compared to the distance between source and receiver (719 m).

B. Bottom and ice coherent reflections

Coherent part of reverberation corresponds to the model where the ocean boundaries are either flat or defined by

coherent components of reflection coefficients. Consider first a case of flat boundaries with high reflectivity. In this case, reverberation coda is a sequence of multiple specular reflections of the emitted pulse from the boundaries with correspondingly increasing time delays and decreasing amplitudes due to the spherical spread and multiple reflection losses. An example of such coda is shown in Fig. 8(a), and some associated paths including specular reflections from ice and bottom at steep (near vertical) incidence (with one and two bottom bounces) are shown in Fig. 8(b). The contribution of direct arrivals, for simplicity, is shown by a PE arrow that replaces three possible types of short-range paths of propagation within the surface channel, a direct path, and two nearly horizontal ones, upward refracted by the gradient layer and the one reflected from ice cover at $\sim 85^\circ$ incidence angle.

It is assumed that ice cover is a flat 2 m-thick elastic layer with a complex reflection coefficient given in Fig. 6. Also assumed is that bottom can be represented as a flat elastic basalt half-space. In this case, the reflectivity at the relevant near-vertical directions for both boundaries are high enough: ~ 0.8 for bottom and ~ 0.87 for ice. This, along with additional enhancement caused by the "4-path effect" for source and receiver located not far from the ice, results in a high reverberation level seen in Fig. 8(a) until times and ranges including up to six bottom bounces (~ 50 km range), i.e., for all ranges and times where the ICEX14 reverberation coda was observed [taken from Fig. 2(a) for the average relative intensity and shown in Fig. 8(a) for comparison].

However, introducing ice roughness changes the shape and reduces the level of the coherent component of the coda significantly, which is shown in Fig. 8(a) by a "flat bottom & rough ice" curve. This is due to reduction of the coherent reflection coefficient shown in Fig. 6 at near-normal incidence. As a result, only the path with no reflection from ice and a single bounce from bottom, even if it is highly reflective (as basalt), contributes to the coherent component of the reverberation coda. In the case of rough bottom, reduction of this component will be even more significant, according to additional coherent reflection loss. The coherent reflection coefficient for basalt half-space with a variable RMS roughness parameter is shown in Fig. 9 as a function of incidence angle. For other input parameters needed in the calculations, density, compressional and shear speeds, typical values were used which are given, for both ice and basalt, in Table I.

The comparison in Fig. 8 leads to several conclusions. First, the model with highly reflective boundaries, which allows only specular reflections at near-normal incidence, can provide an acceptable fit to the reverberation coda observed at medium ranges (and corresponding times). However, introducing the ice roughness, which is necessary for the relatively thick ice conditions, makes the unfit significant even at rather short times and excludes any ice bounces. This means that those bounces should result in mostly non-specular incoherent scattering from ice in directions which are far from near normal, particularly (as discussed

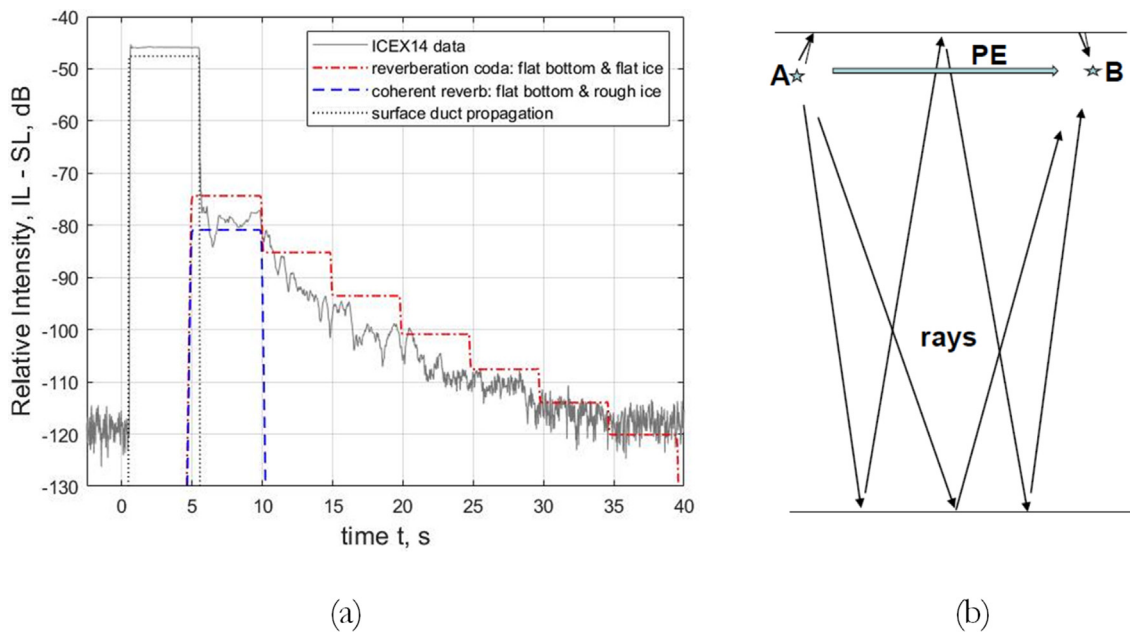


FIG. 8. (Color online) (a) ISEX14 data compared to a model that includes, in addition to direct arrivals, only coherent component of reverberation caused by specular reflections from bottom and ice given their reflection coefficients at steep (near vertical) incidence, with associated paths (b). Bottom is a flat elastic basalt half-space, while ice cover is a flat 2 m-thick elastic layer, either flat or rough.

later, in Sec. IV C) to backscattering in slant directions, and, therefore, considering incoherent reverberation is necessary.

Also, a good fit at short time corresponding to a single bottom bounce [~ 5 – 10 s; see Fig. 8(a)] is possible only with assumption of perfectly flat highly reflective bottom (as a flat water-basalt interface). Figure 9, however, shows that even a small RMS roughness (~ 5 cm) would result in a noticeable reduction of the bottom bounce amplitude, and would worsen the fit of coherent reverberation curve [Fig. 8(a)] to the observed level at short times (5–10 s) corresponding to the first bottom bounce at near-normal incidence, and, therefore, a proper compensation from incoherent component of

bottom scattering is needed. Also, this requires examining angular dependencies of reflection and scattering coefficients for both bottom and ice at slant directions, as well as accounting for acoustic absorption in water column that can be important for slant paths and correspondingly longer ranges.

C. Incoherent scattering effects

In the case of non-flat boundaries, the reverberation time series were calculated using a single scattering approximation that considers arrivals along slant paths which include only one non-specular scattering from bottom or ice, while all others are neglected. The results are shown in Fig. 10(a), and the arrivals, the earliest and strongest ones, are shown in Fig. 10(b), in addition to horizontal and nearly vertical paths discussed earlier and shown in Fig. 8.

Model simulations of reverberation were performed taking into account acoustic absorption coefficient in sea water, 0.2 dB/km at 3.5 kHz, which is a typical value (see Jensen *et al.*, 2011), and corresponds to the loss parameter of water $\delta_{kw} \approx 1.57 \times 10^{-6}$. Dependences of backscattering coefficients on incidence angle for bottom and ice are taken in the form $m_S(\theta) = M(\cos \theta)^\gamma$, assuming unknown strengths M and power exponents γ . The values of these parameters resulted from model-data comparisons are given in Table I. Interestingly, for the ice scattering strength, the best fit is at $\gamma = 2$ which corresponds to well-known Lambert Law.

The reverberation data and model prediction that provides best fit to the data are shown in Fig. 10(a) by solid gray and dotted red lines, respectively. The model result is obtained from a summation of four contributions: near-vertical bottom reflection (dash blue), a -120 dB noise, and

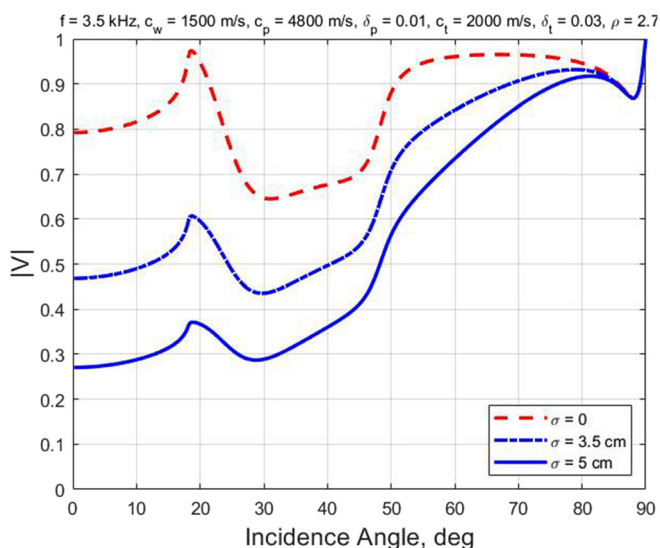


FIG. 9. (Color online) The reflection coefficient as functions of the incidence angle for bottom basalt half-space which is assumed either flat or rough.

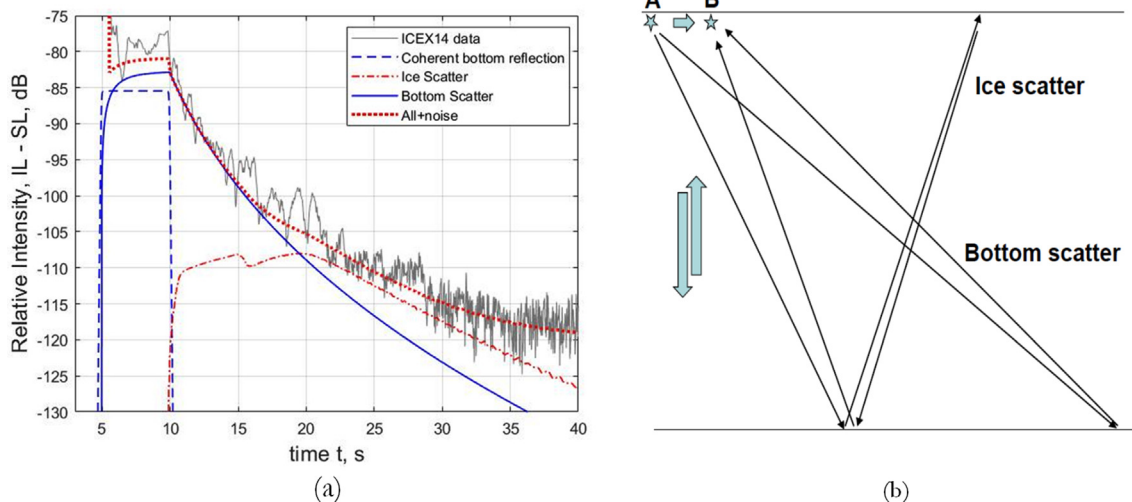


FIG. 10. (Color online) ICEX14 reverberation data-model comparison (a) including coherent bottom reflection and incoherent ice and bottom backscatter arrivals, and associated paths (b) where thick horizontal and vertical arrows replace multipath components shown in Fig. 8.

two slant backscatter mechanisms shown for the bottom and ice scatter contributions by solid blue and dash-dot red curves, respectively. The near-vertical and slant specular reflections are associated with the paths shown in Fig. 10(b). Corresponding reflection coefficients are taken from Fig. 9 (see the curve for basalt with 3.5 cm RMS roughness). The near-vertical coherent bottom reflection is reduced correspondingly [compared to that shown for flat bottom at 5–10 s time in Fig. 8(a)]. However, this reduction is compensated by the bottom scatter incoherent component which also became the dominant mechanism of reverberation (compared to ice scatter) at intermediate times (10–20 s).

Note again that the values of physical and acoustical parameters of ice and bottom used for calculations of propagation and reverberation in this paper are simply representative to outline the required set of the used model inputs. A comprehensive discussion of these inputs for different types of the ocean bottom can be found, e.g., in Jackson and Richardson (2007), Jackson *et al.* (2010), and references therein. In the model of ice cover, we considered only the case of a single homogeneous elastic layer. The models used here to specify the reflectivity of bottom and ice can be generalized to also include effects of poroelasticity and layering in a more consistent way following, e.g., Brekhovskikh (1980), McCammon and McDaniel (1985), Williams (2001). Hope *et al.* (2017), and Chotiros *et al.* (2021). Such generalizations, however, are beyond the scope of this paper.

V. SUMMARY AND CONCLUDING REMARKS

In this paper, we present a model-based analysis of an experiment on midfrequency sound transmission in a deep ice-covered Arctic ocean. Recorded acoustic intensity time series showed a clear direct blast signal (having the shape of ~ 5 s duration emitted pulse) followed by an about 30 s duration long reverberation coda. For consistent model-data comparison, considering a combined effect of several mechanisms is needed, each dominating within its own time

interval. The main result is that each segment of the recorded time series was interpreted by a specific sound propagation or scattering mechanism(s), which was accompanied by an explanation, both qualitative and quantitative.

Figure 11 gives a final comparison of the ICEX14 data with modeling results which include summation of short- and medium-range mechanisms considered in this paper. Short-range transmission loss is controlled by nearly horizontal propagation in the surface channel, including refraction effects in the water gradient layer and reflection from the ice cover.

The direct signal has a level which is slightly varying (within ~ 2 dB bounds). This paper suggests a modeling approach that allows quantifying mechanisms affecting the measured intensity level and its variation over time of observations (~ 5 min). We show that the level is strongly affected by the structure of a surface duct (within 50 m depth) and, particularly, variations in the depth of a thin

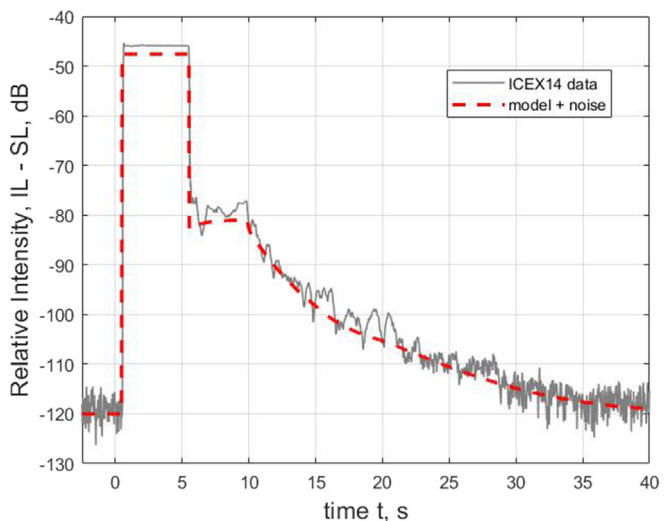


FIG. 11. (Color online) The full time series comparison between measured ICEX14 data and model results.

gradient layer beneath (typically at ~50–60 m depths), reflections from ice, refraction in water, and their interference. An important finding is that the presence of ice cover, either flat or rough, results in additional range dependence [O(10 m)] of transmission loss with a slope up to ~1 dB/m. Potentially, analysis of the direct arrival at ranges where focusing effects of upward refraction become noticeable may provide a base for estimating parameters of the surface duct and its boundaries, the ice cover, and the gradient layer.

Reverberation coda that follows the direct signal and corresponds to medium-range arrivals from steep angles is shown to be strongly affected by reflectivity and scattering strength of the bottom and the ice and controlled by several mechanisms dominating within different time intervals. In the beginning—by first bottom reflection, at intermediate times—by backscatter from bottom, and at the end of the coda—by backscatter from ice. Also shown is that parameters of the bottom significantly affect the level and shape of reverberation signal in all the three time intervals. For instance, the angular-dependent effect of bottom roughness appears important for providing a good fit to reverberation data for two reasons. First, it reduces near-vertical reflection. Second, it also retains the high level for slant reflections needed for understanding why the ice Lambert backscatter contribution is still above noise level that comes to the receiver after two bounces from the bottom.

Generally, we believe that a more comprehensive environmental model could lead to a similar or better results of model-data comparison. Our focus here, however, was to suggest and discuss a simple enough forward model and to show its capability to fit the data using a minimal number of critical environmental parameters. Development of improved inversion model for better inferring environmental properties would be a next step and is a goal for future work. In this paper, the values of physical and acoustical parameters of ice and bottom used for calculations of propagation and reverberation are simply representative so as to outline the required set of model inputs.

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