Journal of
Marine Science and Engineering

Article

Arctic-Type Seismoacoustic Waveguide: Theoretical Foundations and Experimental Results

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Abstract: The results of theoretical analysis and practical implementation of seismoacoustic methods developed for monitoring ice-covered regions in the Arctic are presented and discussed. Special attention is paid to passive seismoacoustic tomography as a unique method of studying the deep structure of the lithosphere and hydrosphere without the use of powerful sources. One of the distinctive features of the considered approach is the use of receivers located on the ice surface to recover characteristics of Arctic-type seismoacoustic waveguide "lithosphere-hydrosphere-ice cover". In passive monitoring, special attention is paid to reducing the noise signal accumulation time required to obtain seismoacoustic wave propagation times, as well as expanding the analyzed frequency bandwidth. The presented results can be used to develop technologies for seasonal and long-term monitoring of the currently observed variability of large areas of the Arctic region due to climatic changes.

Keywords: floating ice; seismoacoustics; ambient noise; flexural-gravity waves; surface waves; Arctic; layered medium

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Citation: Sobisevich, A.; Presnov, D.; Shurup, A. Arctic-Type Seismoacoustic Waveguide: Theoretical Foundations and Experimental Results. *J. Mar. Sci. Eng.* **2024**, *12*, 1060. https://doi.org/10.3390/jmse12071060

Academic Editors: Mark D. Orzech, David A. Hebert and Aleksey Marchenko

Received: 14 May 2024
Revised: 20 June 2024
Accepted: 21 June 2024
Published: 24 June 2024

1. Introduction

Currently, Arctic is becoming the most promising region of the Earth where oil, gas, and other minerals will be extracted [1,2]. For effective development of the Arctic region, it is necessary to study seismoacoustic fields generated by induced geodynamic processes in the system "lithosphere–hydrosphere–ice cover". The mentioned wavefields contain useful information about deep underground structures and hydroacoustic conditions in the region, which makes it possible to develop technologies for monitoring large expanses of water covered by a layer of ice in the Arctic Ocean.

One of the actively developing methods for monitoring inhomogeneous structures is passive seismoacoustic tomography, which is used to study both the deep structure of the lithosphere [3,4] and the hydrosphere [5]. Unlike classical methods, passive tomography uses the ambient noise field as a source of information about the environment rather than signals emitted by powerful low-frequency sources specially placed in the study area [6]. When exploring in the Arctic, standard marine seismic methods face certain difficulties due to the presence of ice. The use of active sources, moreover, invariably faces geo-environmental concerns regarding protected marine fauna [7]. The development of offshore fields, in addition to the direct threat to the environment, does not exclude the possibility of provoking natural and man-made disasters [8,9]. The latter can be caused by various endogenous processes, including those associated with the natural evolution of gas hydrate accumulations [10].

Despite the significant advantages of passive monitoring methods (low cost, technical simplicity, absence of environmental problems), the possibility of their application for solving practical problems largely depends on the measurement conditions. In the case of the considered task of monitoring the layered geophysical environment "lithosphere–hydrosphere–ice cover", it is possible, for example, to use several sensors separately for seismic studies of the lithosphere, for hydroacoustic observations of the water layer and, finally, for monitoring the ice cover. Another more reasonable approach is to use a single sensor mounted on the ice sheet, which allows measuring the seismoacoustic wavefield over a wide frequency range (0.03–1000 Hz), capturing both seismic and hydroacoustic frequency ranges. In recent years, this new scientific trend of placing sensors directly on the ice surface has been actively developed in seismics [11–13]. In addition, it should be noted that in recent decades, new technical solutions have been proposed that allow organizing long-term observations on ice fields in the Arctic. In this case, seismoacoustic data can be collected by autonomous drifting stations [14,15] without human participation and, subject to prompt processing, realize monitoring of changes in the characteristics of the Arctic waveguide. This can be used in the future to solve a practically important task—to estimate the seasonal and multiyear variability of sea ice thickness of freezing seas, including shelf zones. The relevance of the research topic is confirmed by the Chinese Arctic expedition in 2023 and the end of the drift of the newest Russian ice-resistant self-propelled platform in the Arctic in the same year.

Thus, the question of interpretation of seismoacoustic signals measured on the ice and, first of all, the possibility of identifying seismic signals carrying information about the geological structures of the shelf arises. The purpose of this work is to determine what types of waves can be used to monitor the environment in Arctic conditions using seismoacoustic sensors installed on the ice. In this regard, it seems reasonable to develop a standard model of an Arctic waveguide to describe the propagation patterns of both deterministic and random wave disturbances in ice conditions. Experimental verification of a new passive method for monitoring ice cover parameters along extended distances based on the analysis of ambient noise deserves special attention. For this purpose, the results of in situ observations of seismoacoustic wavefields made in various conditions are used.

2. Theoretical Foundations

The brilliant prospects of using elastic waves measured by seismometers and tiltmeters in ice-covered conditions are well known. This is confirmed by numerous experiments in the Arctic [13,16], in which the possibility of determining the parameters of the wave process from the data of sensors installed on the ice was shown. In this case, the Arctic-type waveguide has clearly defined edges such as the seafloor, the ice–water interface, and the ice -snow or -air interface. In this regard, a convenient approach for describing wave processes in an Arctic waveguide is the methods of acoustics of layered media [17]. In contrast to known approaches, where waves penetrating the entire volume of the medium are used for local measurements, such as waves from earthquakes [18], the present study considers normal waves—propagating along medium layers. Their main property is velocity dispersion. In an ice-covered ocean, such waves can propagate for kilometers and, therefore, form a field of ambient noise on the ice, and thus can be used for remote sensing.

2.1. Model Water–Ice–Snow

For the theoretical description of seismoacoustic waves propagating only in a floating ice cover, we can use a simple mathematical model in the form of a solid plate of thickness h, lying on a fluid half-space whose sound speed and density are equal to c_0 and ρ_0, respectively. It is valid when there is no need to take into account the elasticity of the seafloor as was done earlier in [19] and is suitable for deep water, respectively, whose depth H significantly exceeds the wavelength ($kH \gg 1$). The dispersion equation for flexural-gravity waves in such a model has been written out, for example, in [20]. The properties of these waves are determined by joint action of gravity and elastic forces from the floating ice cover. Due to the elastic properties of ice, the wave characteristics of flexural-gravity waves are determined by the thickness of the ice cover as well as by the cylindrical rigidity coefficient. The importance of such waves is due to their role in ice mechanics, including the ability to destroy ice fields [16]. Note that in the literature on ice mechanics [21], it is common to use another expression for flexural-gravity waves for a model in the form of a solid layer lying on a fluid layer of finite thickness H, but not taking into account the compressibility of the fluid ($c_0 \to \infty$), which is valid for low frequencies ($kH \ll 1$). As the frequency increases, the acoustic field in the fluid "joined" by the flexural wave in the plate will change the character of the wave.

Another important factor is the presence of snow cover on the ice, which affects the propagation of the flexural wave and also loads the ice, which can change its local physical characteristics. Accounting for snow in the medium model is a relevant problem [13], which can be solved in the first approximation by introducing a viscous layer covering the ice plate. Then, taking into account the action of inertia and viscous friction forces, the following dispersion equation can be obtained for a floating ice layer covered with snow:

$$Dk^4 + i\omega\eta_s h_s k^2 + \rho_0 g - (\rho h + \rho_s h_s)\,\omega^2 - \frac{\rho_0\omega^2}{\sqrt{k^2 - {k_0}^2}} = 0 \quad (1)$$

where $k = \omega/c$, $k_0 = \omega/c_0$ are the wavenumbers; $g = 9.8$ m/s^2 is the free fall acceleration; $\omega = 2\pi f$ is the cyclic frequency; η_s is the viscosity of snow; $\rho,\ \rho_s$ are the density of ice plate and snow, respectively; $D = E\,h^3/12\left(1-\mu^2\right)$ is the cylindrical rigidity of ice plate, where E, μ are the Young's modulus and Poisson's ratio of ice plate. As follows from Equation (1), the wavenumber k can take complex values. The imaginary part k will provide the coefficient of attenuation of wave motions due to inelastic energy dissipation in the snow layer.

2.2. Model Seafloor–Water–Ice

The ambient seismoacoustic noise generated by Rayleigh surface waves on land is known as Scholte or Stonely waves in underwater conditions. These waves play an important role in the study of geologic structures [3,22,23]. In the context of the Arctic waveguide, where ice cover provides a unique environment for elastic wave propagation, the study of the excitation efficiency of these type of wave is of particular interest. In the present study, we consider a point source acting on the seafloor to model surface waves. To study the spatial energy distribution of the main types of modes in an Arctic waveguide, we will use a horizontally layered model of the "lithosphere-hydrosphere-ice-cover" type medium.

The basis is the dispersion equation for elastic waves propagating in a layered medium consisting of a finite-thickness solid ice layer, a fluid water layer, and a homogeneous solid half-space modeling geological structures [19]. Following [19], we assume that the layered model consists of a solid layer of thickness h (ice), an infinite solid half-space occupying the region $z < -h'$, and a fluid layer of thickness $H = h' - h$. The r axis coincides with the horizontal direction, in which all layers are homogeneous. We denote c_l, c_t as the velocities of propagation of longitudinal and transverse waves in the solid layer; c_0 as the speed of sound in the fluid; ${c_l}'$, ${c_t}'$ as the velocities of longitudinal and transverse waves in the solid half-space. The velocities are material-dependent and can be expressed in elastic parameters. The density of the medium is denoted as $\rho,\ \rho_0$ and ρ' for ice, water, and geologic structures, respectively. In the first stage of the study, the surface of the layered half-space is assumed to be stress-free. We will use strict expressions to describe small displacements $\vec{u} = \{u_r, u_z\}$ in solids and fluids. These are Newton's second law and Hooke's law for an isotropic solid, as well as linearized equations of hydrodynamics, which can be reduced to wave equations by introducing scalar and vector potentials for each of the media of the layered model $\vec{u} = \mathrm{grad}\,\varphi + \mathrm{rot}\,\vec{\psi}$ (in fluid, there are no shear deformations, so the vector potential is equal to 0). In two-dimensional formulation, it is enough to use expressions for plane waves. We will search for solutions of the equations by the method of Fourier integral transformations:

$$\begin{aligned} \varphi(r,z,t) &= \int_0^\infty \left[A(k)\, e^{i\alpha_l z} + B(k)\, e^{-i\alpha_l z}\right] e^{ikr-i\omega t} dk \\ \psi(r,z,t) &= \int_0^\infty \left[C(k)\, e^{i\alpha_t z} + D(k)\, e^{-i\alpha_t z}\right] e^{ikr-i\omega t} dk \end{aligned} \quad (2)$$

where $\alpha_i^2 = k_i^2 - k^2$ at $i = l, t, 0$; $k_i = \omega / c_i$—wavenumber; c—phase velocity. The coefficients A, B, C, D should be determined from the boundary conditions, the first of which, in the case of the action of a point source at the seafloor–water boundary, will be of the following form:

$$\sigma'_{zz} = \sigma_{0zz} - \frac{F}{2\pi r}\delta(r) \quad (z = -h') \quad (3)$$

where σ_{0zz}, σ'_{zz} are the perpendicular components of the stress tensor in water and seafloor, respectively; F is the amplitude of the point impact; $\delta(r)$ is the delta function. Standard conditions of the absence of tangential components of the displacement tensor in water and continuity of the vertical component of displacements at the seafloor boundary are added to it. Similar boundary conditions, but in the absence of a source, need to be written at the water–ice boundary:

$$\sigma_{zz} = \sigma_{0zz};\ \sigma_{zr} = 0;\ u_z = u_{0z} \quad (z = -h) \quad (4)$$

As a result, taking into account the conditions at the free boundary, we obtained a system of eight equations, which we solved using computer algebra methods. The rather complicated form of the final expressions for the displacement components does not allow us to provide them in full here, so we will limit ourselves only to analyzing the obtained solutions.

The dispersion curves were calculated numerically for different values of the parameters characterizing the medium c_l, c_t, c_l', c_t', h, and H. It was found that the type of dispersion dependencies is quite sensitive to the choice of these values. In our work, we consider the case where the velocities of longitudinal and transverse waves in a seafloor half-space c_l' and c_t' exceed the speed of sound in water c_0. In the general case, several families of wave modes are distinguished: (I) flexural-gravity wave, note that in [19], in contrast to Equation (1), the gravitational force, which leads to a change in dispersion properties to the gravity wave [16,24], was not taken into account; (II) Scholte–Stonely-type wave corresponds to the so-called bottom surface wave, which has no critical frequency and propagates along the boundary between the water layer and the seafloor geological structures; (III) normal waves of a plate formed by a layer of ice – Lamb modes; (IV) hydroacoustic modes. The study of (III) and (IV) modes is beyond the scope of this paper. Figure 1 shows the results of calculating dispersion curves with the model parameters specified in Table 1.

Table 1. Parameters of the layered medium model.

	Density, kg/m^3	**Viscosity, Pa·s; Velocity, m/s**	**Thickness, m**
Snow	$\rho_s = 300$	$\eta_s = 100$	$h_s = 0.5$
Ice	$\rho = 900$	$c_l = 4000$; $c_t = 1900$	$h = 2$
Water	$\rho_0 = 1000$	$c_0 = 1500$	$H = 18$
Seafloor	$\rho' = 2600$	$c_l' = 5250$; $c_t' = 2900$	∞

Moreover, the calculation results for the full model of the Arctic waveguide, which takes into account the solid seafloor, are compared with the calculation results within the framework of Equation (1), where the effect of gravity and the presence of snow cover are taken into account. As can be seen within the parameters of the medium model used, gravity begins to influence the phase velocity at frequencies below 0.1 Hz. Consideration of snow cover begins to affect wave speed at frequencies above 40 Hz, although it cannot be called significant.

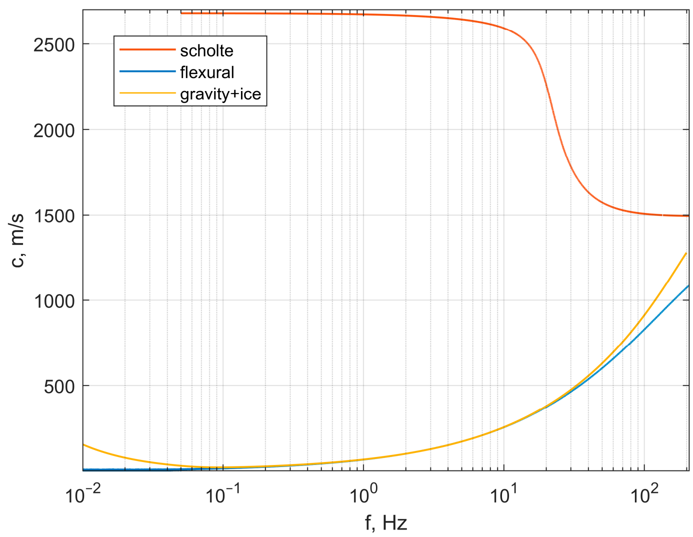


Figure 1. Phase velocity of the flexural-gravity and bottom surface waves in Arctic-type waveguide, yellow color shows the calculation results taking into account action of gravity and presence of snow cover.

Of particular interest is the study of the amplitude distribution of individual modes along the depth of the layered model to evaluate promising areas for signal acquisition in in situ experiments. In this case, we will consider only the vertical component of displacements since only such measuring equipment was used in the present work. The results of calculating the dependence of the vertical component of the displacement field $u_z(z)$ generated by a point source acting on the seafloor on the depth are presented in Figure 2 for two frequencies at the parameters of the layered model specified in Table 1. Figure 2a shows the calculations for the flexural-gravity wave. From its analysis, it follows that the maximum energy of the wave is concentrated in the ice cover region but shifts to the seafloor–water boundary as the wavelength decreases. Figure 2b shows the calculation results for a bottom surface wave, the maximum of which is located at the seafloor–water boundary but may shift to the ice cover at longer wavelengths.

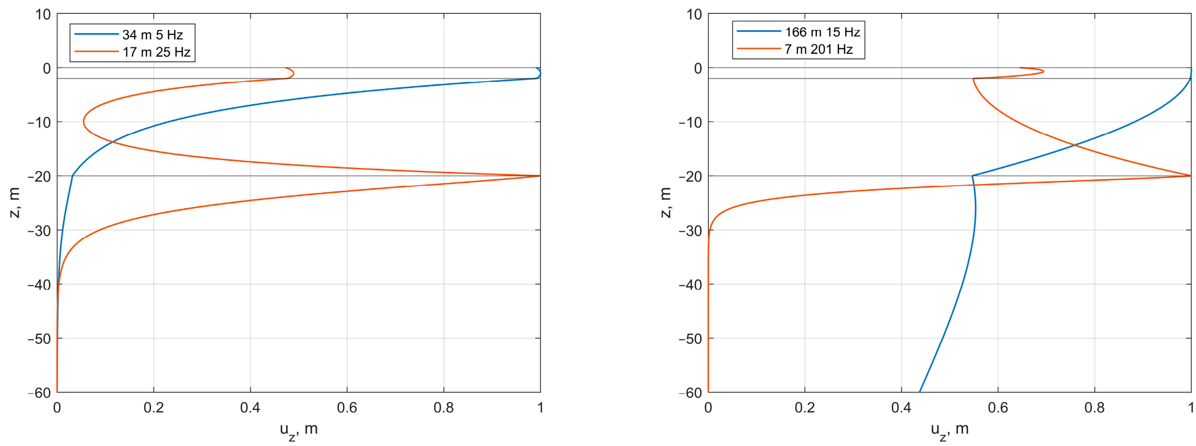


Figure 2. Amplitude of vertical displacements depth distribution in the layered model for: flexural-gravity (**a**) and bottom surface waves (**b**). The wavelength and frequency of dispersive waves are shown in the legend. Horizontal lines show the boundaries of the media in the layered model.

Thus, the results of mathematical modeling indicate the theoretical possibility of measuring the bottom surface wave on the ice surface, which greatly simplifies the technical side of experimental work in the water area covered with ice when it is necessary to study the geological structures of the seafloor. The following section is devoted to the possibilities of practical use of this result.

3. Results of Full-Scale Experiments

By the example of processing experimental data obtained with the help of geophones and a new class of buoys of the freezable type installed on the ice cover and measuring the vertical component of the vibrational velocity, the possibility of estimating the frequency and time characteristics of individual mode components of the full seismoacoustic field is demonstrated. As was shown in the mathematical model of the Arctic waveguide, several types of waves are possible, each of which carries information about the corresponding propagation medium. When measuring in ice conditions, the problem arises of separating the different components in the fully measured wavefield in order to further evaluate the characteristics of seafloor geological structures and water media. In addition, determination of the different informative characteristics of waves is possible without the use of an active signal source, indicating that the application of passive medium monitoring is promising. In this section, we demonstrate results of the separation of mode components of the seismoacoustic field in active and passive regimes in the conditions of an ice-covered water area.

3.1. Equipment

Sea ice seismoacoustics is a relatively new, rapidly developing scientific field that requires the use of most innovative and, at the same time, cost-effective measurement and data acquisition systems [15]. An autonomous geohydroacoustic ice buoy, a detailed description of which is presented in [14], is used to measure low-amplitude broadband fluctuations of the ice cover. For use in extreme Arctic conditions associated with low temperatures and powerful ice pressure, the measuring element of the ice-class system should be well protected from external factors. To solve this problem, a special instrument housing was developed at the Schmidt Institute of Physics of the Earth with the participation of R-sensors LLC (Dolgoprudny, Russia), which accommodates a data logger NDAS-8224, a storage device, a broadband molecular-electronic seismometer of R-sensors CME4211 type, and a battery. It provides high shock resistance and the possibility to install instrument in exceptional conditions, for example, on the ocean floor or on ice cover. The housing is made of thick duralumin in the form of a cylinder with a diameter of 130 cm at its widest point and a height of 40 cm. It makes it extremely easy and fast to deploy the instrument into the ice cover using a classic ice auger. The housing is hermetically sealed, which is very important for a pressure-sensitive molecular–electronic sensor. Tests have shown that the housing can withstand hydrostatic pressure at depths of up to 300 m. It should be noted that the geohydroacoustic ice buoy was originally designed for the application of a broadband seismometer in ice conditions. For this reason, it is of interest to compare the signals measured by the buoy, basic seismometer SM3-OS, Microseism LLC (Obninsk, Russia) and a conventional geophone GS-ONE LF, Geospace Technologies Eurasia LLC (Ufa, Russia) (see Table 2).

Table 2. Parameters of seismic equipment used during the experiments.

Model Name	Frequency Band, Hz	Sensitivity, V/(m/s)
CME-4211	0.03–50	~2000
SM3-OS	0.03–10	~4000
GS-ONE LF	4.5–1000	~100

3.2. Active Mode

Experimental work was carried out in the Naismeri Bay of Lake Ladoga, Republic of Karelia, Russia, at the test site of Concern Oceanpribor JSC (Saint Petersburg, Russia). We developed a scheme for observing seismoacoustic signals in the conditions of the water area covered with ice in the form of an isosceles triangle with a side of one km and a base of 200 m. It includes three main measuring points, each of which consisted of sensors on the water floor, in the water column and on the ice, as well as points of signal excitation by different sources (see Figure A1). The depth of the lake varied within the deployment from 10 to 20 m, the ice thickness was 40 cm everywhere, and the thickness of the snow layer varied from five to 10 cm. An SM3-OS vertical seismic receiver was installed on the ice surface (Figure A2a), and a CME4211 vertical molecular-electronic bottom receiver was installed on the water floor. Three-channel RefTek 130B recorders were used to measure the signals obtained with the above equipment, which ensures temporal synchronization of different observation points with the required accuracy. To excite the bottom surface wave, a 32 kg weight was dropped from a height of 20 m to the water floor, and a firecracker (~40 g of gunpowder) was detonated near the water floor. A typical waveform at a distance of one kilometer from the source is shown in Figure 3 for the frequency range of 6–15 Hz. Analysis of the recordings shows that the signals received on the ice and on the water floor are almost completely identical. It follows that the wave excited in the water floor and carrying information about geological characteristics can be registered on the ice cover surface. It should be taken into account that the initial signal on the ice (shown in gray in Figure 3 from above) is complicated by intensive low-frequency disturbances, which may impose limitations on the possibility of registration of the bottom surface wave by receiver installed on the ice.

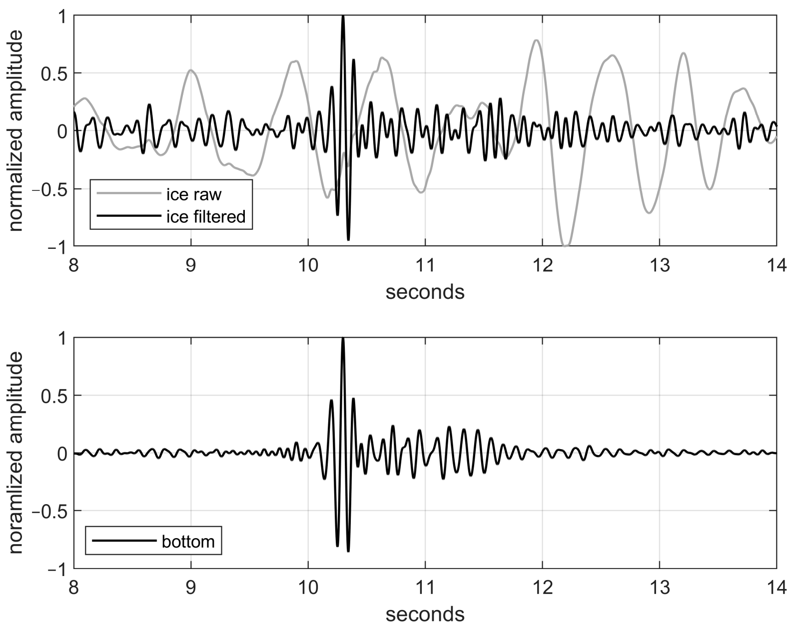
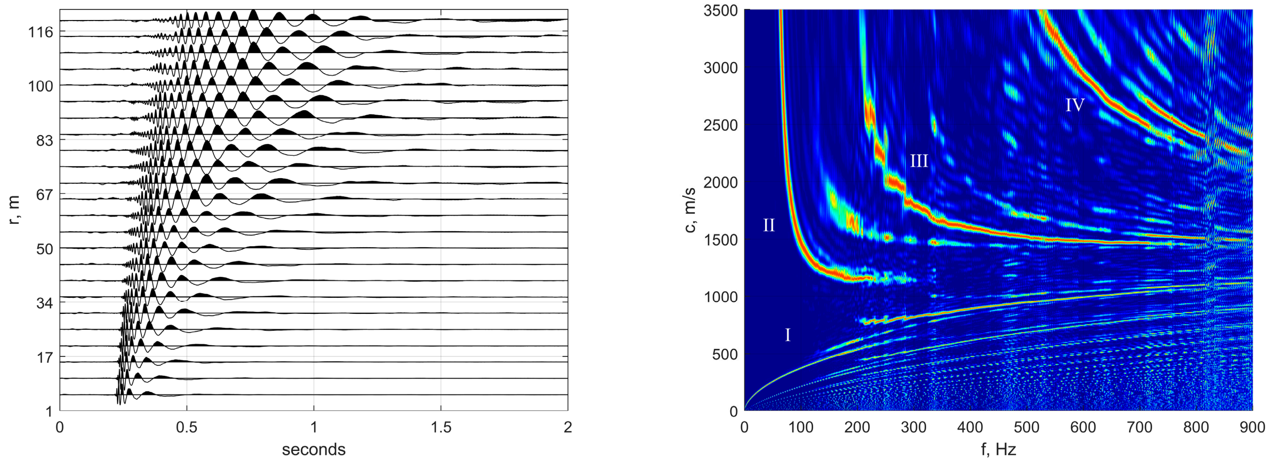


Figure 3. Example of synchronous recordings of a signal from a point source acting on the water floor in ice conditions by a bottom seismometer (**bottom**) and a seismometer installed on ice (**top**).

Thus, the results of the full-scale experiment in ice conditions using a point source near the water floor indicate the reliability of the theoretical constructions. For specific experimental conditions, the signals in a certain frequency range measured by the recievers installed on the ice and on the water floor proved to be identical. It should be taken into account that dispersion dependences are significantly affected by the physical parameters of the medium. The possibility of estimating the dispersion of the bottom surface wave is of interest for further studies.

At the next stage of the study, a multichannel group of receivers was used to measure signals on ice cover. The basis of the measurement system was a seismic station, DAQlink4, which was configured to operate in the continuous monitoring mode with a recording frequency of 2000 Hz. A signal cable containing 24 receivers spaced five meters apart was connected to the station. The receivers used were GS-ONE LF vertical geophones (Figure A2b). The receiver system was placed as a linear group with a total length of 120 m in the spring of 2024 on the ice of the Klyazma Reservoir, Moscow region, Russia, at the MSU hydroacoustic test site at a distance of about 200 m from the shore. The depth of the water layer at the site was ~6.7 m, ice thickness ~40 cm, and snow cover thickness ~30 cm. The impact with a sledgehammer weighing four kilograms on the ice at a distance of about 10 m from the first receiver was used as a source of the signal. The results of the experiment are shown in Figure 4a (the vertical axis shows the distance along the line with the source), from which it follows that the amplitude of the signal decreases with distance due to the increase in the duration of the signal caused by dispersion.



(**a**) (**b**)

Figure 4. Example of a multichannel recording of a signal on ice cover from a source acting on ice (**a**) and phase velocities obtained from time–frequency analysis of the recordings (**b**), mode numbers are marked following Section 2.2.

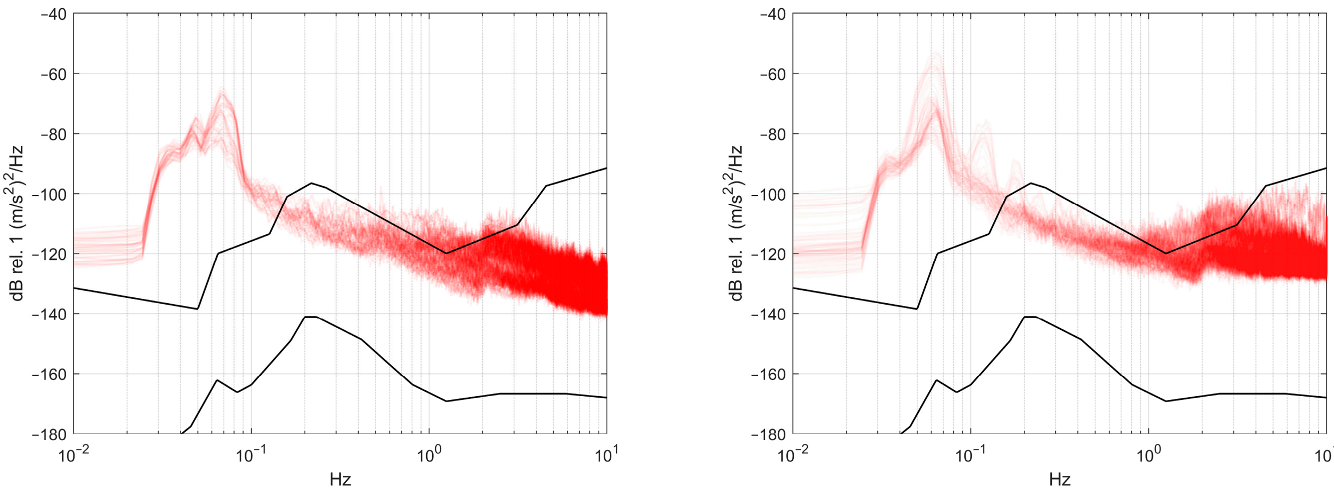
To investigate the dispersion of wave velocity measured at the ice surface, an *f-k* analysis of the multichannel recording was performed, and the results are presented in Figure 4b. It follows that the full received wavefield has a complex structure in which separate mode components can be distinguished. The slowest mode is the ice plate flexural wave (I). Its velocity varies from 0 at low frequencies to ~1000 m/s at 1000 Hz and contains information about the ice parameters—thickness and cylindrical rigidity. Faster waves, with high-frequency asymptotic at ~1500 m/s, are probably hydroacoustic modes. All other waves have no upper velocity limit and apparently belong to the Lamb modes of the ice plate. It can be seen that the signal-to-noise ratio is sufficient for automatic picking of phase velocity values, which can then be used to estimate the medium parameters based on the Arctic waveguide model.

The results of experiments with powerful signal sources showed the possibility of mode separation in the full wavefield, as well as the possibility of bottom wave registration on the ice cover surface. At the same time, in situ observations indicate that the ice cover is an active dynamical system experiencing low-frequency oscillations that complicate the development of Arctic waveguide monitoring methods, which is confirmed by the results of other researchers [11]. In the next section, the seismoacoustic noise parameters of floating ice are studied.

3.3. Passive Mode

The initial data are ambient noise fields measured by spatially separated sensors located on the ice surface. Signal processing is based on spectral-correlation analysis of the observed seismoacoustic noise. In this case, it is possible to estimate the characteristics of the Green's function of the receiving points, i.e., to obtain information about the seismoacoustic field as if it were emitted and received at these points. This approach is convenient because it does not require the use of powerful low-frequency sources. The first step is to study general characteristics of the ambient seismoacoustic noise observed in the ice cover. For this purpose, unique data obtained in the Arctic will be used.

The material for this section was a short field trip in the spring of 2023 to Alexandra Land Island of the Franz Josef Land archipelago as part of a comprehensive expedition of the Russian Geographical Society. The receiving system was placed on landfast ice in the water area of Severnaya Bay at a distance of about 500 m from the shore. As a result, a continuous recording of seismoacoustic noise of various origins formed in the Arctic sea ice was obtained. The same multichannel geophone system described above was used as measurement equipment. The duration of measurements was 29.5 h. When measuring vertical ice oscillations, the main contribution to the wavefield on ice is associated with flexural-gravity-type wave modes generated by wind, currents, gas bubbles hitting the ice surface, or ice shaking—when internal deformation of the plate due to relative drift, ballooning, and thermal expansion of the ice leads to the formation of cracks [16]. Figure 5 presents the power spectral density of seismoacoustic noise arising in the ice cover, which was measured in 2023 using a vertical geophone (Figure 5a), taking into account the instrument response and a broadband seismometer installed in a geohydroacoustic ice buoy (Figure 5b) in 2021 on the ice in Dezhnev Bay, Franz Josef Land. To calculate the power spectral density, we used the entire available record, lasting ~24 h, and each of the curves in Figure 5 corresponds to one hour. It can be concluded that, in general, the noise spectra show comparable values, and thus, the low-frequency geophone is as reliable as a seismometer in the task of measuring intense seismoacoustic ice noise. At the same time, a sufficiently high level of ambient noise allows us to proceed to the task of using it as a source of useful information about the structure of the medium.



(**a**) (**b**)

Figure 5. Comparison of the spectral parameters of seismoacoustic noise in the Franz Josef Land area measured on the ice surface by a geophone (**a**) and a broadband seismometer (**b**), with the Peterson models of low (NLNM) and high (NHNM) seismic noise levels shown in black.

The next stage of the work is to investigate the applicability of the passive regime of seismoacoustic wave velocity estimation. In this case, the ambient seismoacoustic noise generated by random sources of natural or anthropogenic origin is used as a useful signal source. It was shown [23] that the cross-correlation function of seismoacoustic noise measured by a pair of sensors, when averaged over a long period of time, can represent the Green's function. Then, only sources located near the straight line connecting the two receivers will contribute to the final cross-correlation function, and it will have a symmetric form with respect to zero time delay, which will eventually allow us to estimate the travel time between the pair of sensors used. This technique is called seismic interferometry, and the task of applying it to data observed on ice is quite relevant.

Passive fieldwork was conducted on the ice of Lake Baikal, Irkutsk region, Russia, in the vicinity of the geodynamic polygon of the Institute of the Earth's Crust. During the period of the experiment, the ice thickness was about 1 m, and the ice surface was free of snow and slightly thawed during the daytime. An ice group consisting of several autonomous geohydroacoustic ice buoys was used as the main geophysical instrument. Thus, a seismoacoustic antenna with an aperture of ~1.2 km, consisting of six autonomous sensors and one three-component seismometer, was formed on the ice-covered lake. The depth of the lake under the group was about 300 m.

The purpose of the following section is to demonstrate that the results obtained using the cross-correlation function can be even better than those obtained using an active source. Passive nondestructive testing methods are based on the possibility of estimating the Green's function by analyzing the cross-correlation function of noise fields in the investigated area. A sufficiently large amount of scientific literature is devoted to the physical and mathematical aspects of this, among which we can highlight [3,4]. Since the cross-correlation function integrates the contribution of all noise sources, the most favorable influence on the results of correlation processing comes from the procedures of signal amplitude "normalization" and spectrum whitening, which allows us to reduce the negative influence of isolated sources and expand the frequency content. Figure 6 (top) shows the 1 h cross-correlation function calculated using special preprocessing procedures [23] and averaged over 2 days for a pair of sensors located at a distance of ~ one km. The blue vertical lines denote the velocity of ~400 m/s.

One of the criteria for the reliability of the estimates is the presence of two peaks of the correlation function, symmetric with respect to zero delays, corresponding to the time of wave propagation along the path between the receivers as if the signal source were at each of the receiving points. To show this, a spectrogram was calculated (Figure 6 below). The spectrogram clearly shows the symmetry with dispersion characteristic of the flexural-gravity wave mode. Thus, the obtained experimental data on the propagation velocity of this wave can be used to solve the inverse problem of restoring the ice cover characteristics. In this case, the elastic characteristics of the ice are averaged over the length of the base, i.e., over the distance between the seismometers. Similar to [13], we used the Bayesian inversion method to obtain the theoretical curve closest to the experiment. The best result was obtained with the following parameters of the model ice layer $h = 1$ m; $c_l = 3800$ m/s; $c_t = 2200$ m/s, for which we calculated the group velocity and then the travel time, which is shown in black in Figure 6 (bottom). In contrast to [13], we used a pair of individual receivers separated by a sufficiently large distance rather than a group of geophones, which does not allow us to estimate the phase velocity dispersion in passive mode. This requires imposing additional conditions when solving the inverse problem but allows us to implement monitoring of large ice areas in the future.

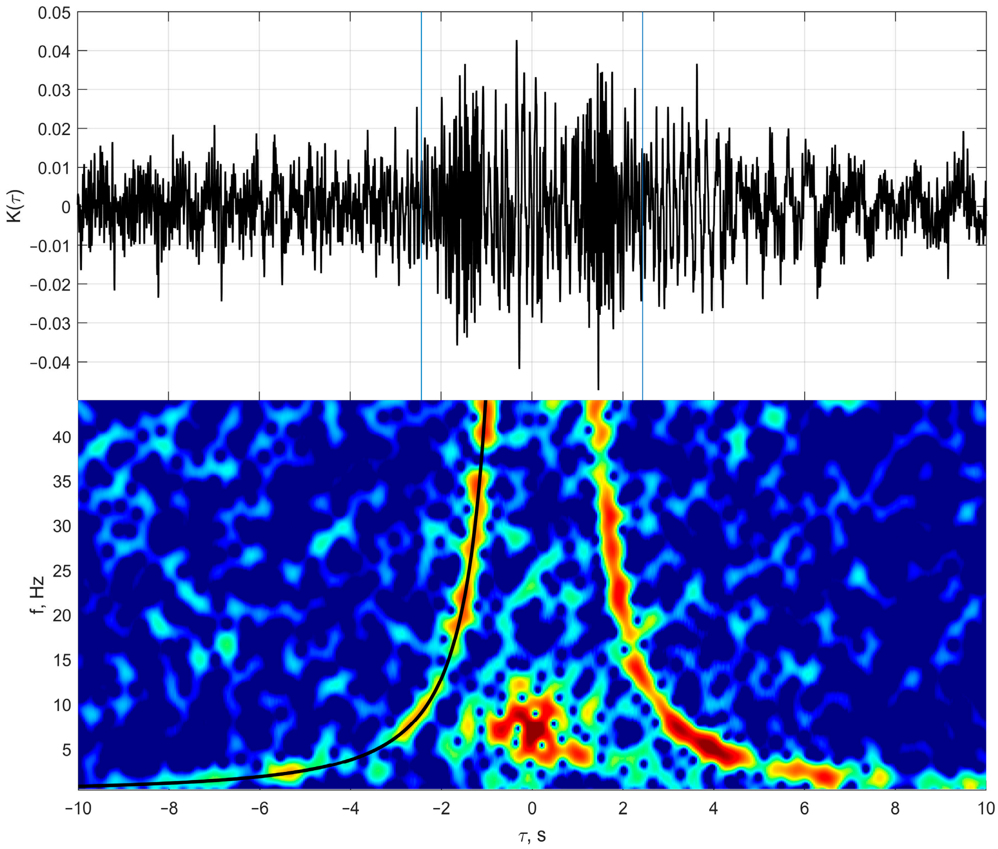


Figure 6. Cross-correlation function of sea ice noise averaged over ~48 h for an interstation distance of 1 km (**top**); spectrogram of the cross-correlation function (**bottom**) and theoretical flexural wave dispersion curve (black line).

4. Discussion

Theoretical and experimental studies of the features of seismoacoustic signal propagation in ice-covered water area conditions have been carried out, which make it possible to develop technologies for monitoring the environment in the Arctic region of great importance. Within the framework of the standard mathematical model of the Arctic waveguide in the form of "lithosphere-hydrosphere-ice cover", the action on the seafloor of a point source, which generates a bottom wave of surface type, is considered. It is shown theoretically and confirmed in full-scale experiments that the parameters of this wave, which carry information about geological structures, can be estimated by means of a sensor installed on ice at depths of up to 20 m. And the use of a multichannel receiver system allows all modes of the Arctic waveguide to be separated. At the same time, in real natural conditions, the solution to this problem is greatly complicated by the presence of low-frequency noise on the ice at frequencies up to 6 Hz, existing regardless of the region of study. On the other hand, intense ice noise can be useful for estimating the physical parameters of the ice cover. Using the method of noise interferometry and a pair of new generation geohydroacoustic ice buoys, the possibility of measuring the group velocity of the flexural-gravity wave in the ice cover along a sufficiently long trace ~1 km at the accumulation of the noise signal during a day was shown. The equation to describe the velocity dispersion of the flexural-gravity wave in the presence of snow cover in the model is written out, and it is concluded that its consideration has a greater influence on the wave attenuation than on the phase velocity. This does not mean that the snow cover will not lead to large errors in the inversion of velocity into the ice cover parameters. The performed inversion of the passive experiment data showed agreement with the results of direct contact measurements.

The authors consider the prospects for further research to be the reduction of the required time of noise signal accumulation due to the optimization of processing methods and the expansion of the frequency range analyzed in passive mode for the study of other modes of the Arctic waveguide. The developed technology for monitoring the physical parameters of the ice cover in an autonomous mode, which does not require human participation, appears to be quite promising, especially for application in the extremely harsh conditions of the Arctic.

Author Contributions: Conceptualization, A.S. (Alexey Sobisevich); methodology, A.S. (Andrey Shurup); software, D.P. and A.S. (Andrey Shurup); validation, A.S. (Andrey Shurup); formal analysis, D.P.; investigation, D.P.; resources, A.S. (Alexey Sobisevich); data curation, D.P.; writing—original draft preparation, D.P.; writing—review and editing, A.S. (Alexey Sobisevich) and A.S. (Andrey Shurup); visualization, D.P. and A.S. (Alexey Sobisevich); supervision, A.S. (Andrey Shurup); project administration, A.S. (Alexey Sobisevich); funding acquisition, A.S. (Alexey Sobisevich). All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Russian Science Foundation, grant number 22-77-00067.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

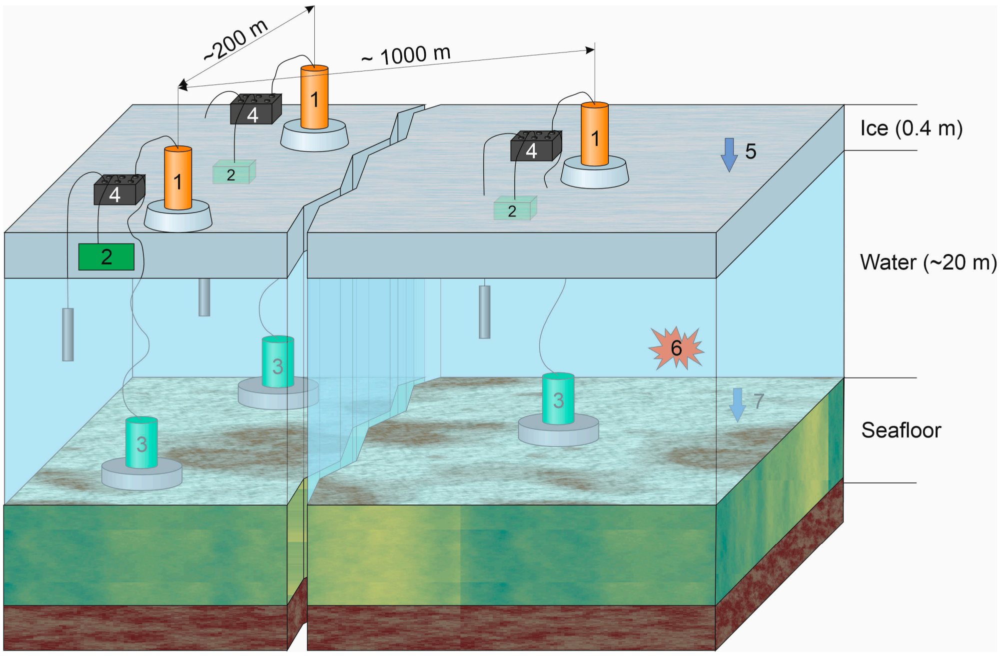
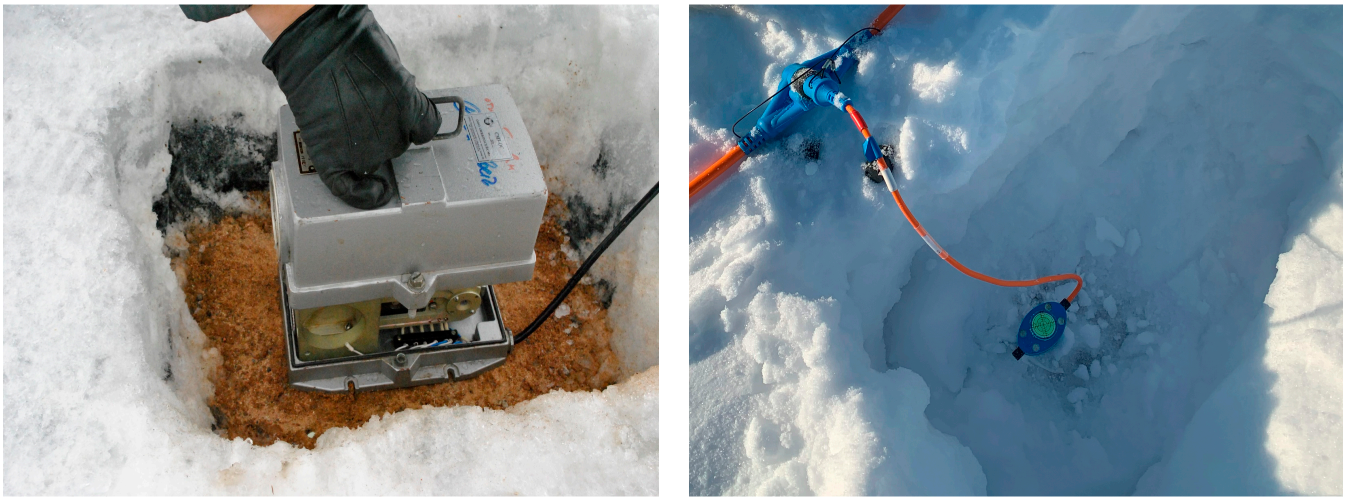


Figure A1. Seismoacoustic experiment in the ice conditions deployment schematics: 1—geohydroacoustic ice buoy; 2—SM3-OS vertical seismometer; 3—CME-4211 molecular–electronic seismometer; 4—RefTek signal recorder; 5—ice impulse source; 6—underwater point source; 7—seafloor impulse source.



(**a**) (**b**)

Figure A2. Illustration of sensor deployment for measure seismoacoustic signals on the floating ice: SM3-OS vertical seismometer (**a**); GS-ONE LF vertical geophone (**b**).

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