Modeling the underwater acoustic communication under ice cover on the Arctic shelf

M V Volkov\textsuperscript{1,2,3}, T S Kalinina\textsuperscript{2}, A A Lunkov\textsuperscript{1,2} and V G Petnikov\textsuperscript{1}

\textsuperscript{1} Prokhorov General Physics Institute of the Russian Academy of Sciences, 38 Vavilov st., Moscow 119991, Russia
\textsuperscript{2} Bauman Moscow State Technical University, 5 2\textsuperscript{nd} Baumanskaya st., Moscow 105005, Russia
\textsuperscript{3} E-mail: volkovmv2@student.bmstu.ru

Abstract. Numerical simulations of the underwater acoustic communication are carried out for a shallow water waveguide with a rough ice cover. The acoustic model is based on a coupled normal mode approach. Binary phase-shift keying is implemented to code the information. The bit error rate in an ice-free waveguide is found to be an order higher than in the case of a rough ice cover. The reason for that is the difference between impulse responses. The impulse response of the ice-covered channel is narrower than in the unperturbed case, which is due to the increased energy transfer from the lower modes to the higher, strongly attenuating modes.

1. Introduction
The offshore development of the Arctic shelf is an actual problem, which includes the monitoring of the underwater environment. Underwater acoustic communication (UAC) can be the only year-round information transmission system that is able to operate under an ice cover. Sound waves allow information transfer between autonomous stations and autonomous underwater vehicles (AUV) intended to record various environmental parameters [1]. In this paper, underwater acoustic communication in the presence of ice cover is considered in numerical simulations. In comparison with previous papers on UAC, the simulations are carried out for a shallow water waveguide with a rough lower ice boundary. Real ice profiles were obtained from the upper looking sonar data [2].

2. Acoustic waveguide model
The model of the arctic acoustic waveguide is shown in Figure 1. To simulate UAC, the waveguide transfer function (impulse response) is calculated in the frequency band from 500 to 1000 Hz. The acoustic model is based on a coupled normal mode approach neglecting the 3D scattering effects. In this model, the sound field complex amplitude is represented as the following sum [3]
\begin{equation}
P(r, z) = \sum_{m} C_{m}(r) \frac{\psi_{m}(r, z)}{q_{m}(r)} \exp \left( i \int_{0}^{r} q_{m}(r') dr' \right)
\end{equation}
Where $\psi_{m}(r, z)$ and $\xi_{m}(r) = q_{m}(r) + i \gamma_{m}(r)/2$ are the local eigenfunctions and eigenvalues, respectively, which are found by solving the Sturm-Liouville problem for each waveguide cross-section
\begin{equation}
\frac{\partial^{2} \psi_{m}(r, z)}{\partial z^{2}} + \left( k(r, z)^{2} - \xi_{m}^{2}(r) \right) \psi_{m}(r, z) = 0
\end{equation}
Here \( k(r, z) = \omega / c(r, z) \) is the acoustic wavenumber, \( \omega = 2\pi f \) is the sound frequency, \( c(r, z) \) is the sound speed profile in the water.

At the water-ice and water-bottom boundary, the impedance boundary conditions are set as

\[
\left[ \psi_m(r, z) - \frac{i\omega \rho}{Z_{\text{ice},m}(r)} \frac{\partial \psi_m(r, z)}{\partial z} \right]_{z=h} = 0
\]

\[
\left[ \psi_m(r, z) + \frac{i\omega \rho}{Z_{\text{bot},m}(r)} \frac{\partial \psi_m(r, z)}{\partial z} \right]_{z=H} = 0
\]

Input impedances \( Z_{\text{ice}} \) and \( Z_{\text{bot}} \) are calculated according to [4].

To find the mode amplitudes \( C_m(r) \) a system of differential equations is solved

\[
\frac{dC_m(r')}{dr'} = -\frac{\gamma_m}{2} C_m(r') + \sum_{n} b_{mn}(r') \left[ \frac{q_m}{q_n} \right]^{1/2} \exp\left( i \int_{0}^{r'} q_n(r'', f) - q_m(r'', f) dr'' \right) C_n(r')
\]

with initial conditions \( C_m(0) = \psi_m(0, z_s) \).

**Figure 1.** Numerical experiment setup, where \( H \) is the depth of the water layer without ice, \( h(r) \) is the position of the lower ice boundary (the upper boundary is assumed to be smooth), \( z_s \) is the depth of the sound source, \( z_r \) is the depth of the receiver.

Here \( b_{mn} \) is the coupling coefficients between normal modes, that can be written as follows.

\[
b_{mn} = \frac{q_n}{2q_m} B_{nm} - \frac{1}{2} B_{mn}, \quad \text{with } m \neq n
\]

\[
B_{mn} = \int_{0}^{\infty} \frac{\rho(z)}{\rho(z)} \psi_m \frac{\partial \psi_n}{\partial r} dz \approx \int_{h}^{H} \psi_m \frac{\partial \psi_n}{\partial r} dz
\]

The acoustic waveguide impulse response is obtained by Fourier synthesis of the complex amplitudes (1) that depend on sound frequency.

\[
h(t) = \int P(\omega; r, z) \exp(i\omega t) d\omega
\]

UAC is simulated for one of the shallow water regions of the Kara Sea. The water depth is constant and equals to 30 m. Sound speed in water is 1440 m/s for all depths. Longitudinal and shear wave speeds in ice are 3500 m/s and 1800 m/s, respectively. Ice density is 920 kg/m\(^3\). The sea bottom is considered as a liquid homogeneous halfspace with the following parameters: sound speed of 1600 m/s, density of 1600 kg/m\(^3\), and the absorption coefficient of 0.33 dB/\( \lambda \). The wideband acoustic source depth is 15.5 m. The receiver depth is 15 m. The maximum horizontal range between source and receiver is 5000 m.

Figure 2 shows the depth-averaged transmission loss vs. range calculated using a normal mode approach and ray approximation for an ice-covered waveguide. Constant ice thickness is assumed.
Both methods give very close results, which means that the calculations made in two different ways are correct.

![Figure 2. Propagation loss at a fixed ice thickness (2m).](image)

One realization of the ice lower boundary roughness taken from the database [2] is presented in Figure 3. The average thickness of the ice cover along the acoustic track is 1.43 m, and the standard deviation is 0.76 m. This realization is used for numerical simulations of UAC via the normal mode method.

![Figure 3. The roughness of the ice cover the lower boundary.](image)

3. Underwater communication simulation and results
The information signal is modulated using Binary Phase Shift Keying (BPSK) [4]

\[ s(t) = \cos(2\pi f_0 t + m(t)\pi) \]

Where \( f_0 \) is a carrier frequency, \( m(t) \) is an information sequence consisting of \( \pm 1 \). The frequency \( f_0 \) is chosen to be rather low (750 Hz) due to the strong attenuation of acoustic waves at higher frequencies [3,5]. The transmission sequence is consisted of 2444 symbols. Each symbol is transmitted for 2.5 carrier periods, which corresponds to a maximum bit rate of 300 bps.

To calculate the signal at a receiver, the convolution of a waveguide impulse response with an information signal is implemented

\[ \tilde{s}(t) = \int_{-\infty}^{\infty} h(t - \tau)s(\tau)d\tau \]

The UAC is simulated for an ice-free and ice-covered waveguide. Figure 4 illustrates the impulse responses for both cases. As one can see, in the presence of rough ice cover, the impulse response of the channel becomes narrower than that in the unperturbed case, which is due to the increased energy transfer from the lower modes to the higher, strongly attenuating modes.
Figure 4. Impulse responses of two information channels: unperturbed waveguide (a), for one of the rough ice cover realizations (b)

Figure 5 shows the calculated soft output for two cases of underwater communication. The soft output displays the information signal complex amplitude passing a waveguide. Note that in a waveguide without ice cover, significant uncertainty in the received signal is observed, which is related to inter-symbol interference due to the waveguide dispersion. However, in the presence of ice cover, two groups of symbols can be separated more accurately, so there is less intersection between neighboring bits. The reason for this difference is that the impulse response of a waveguide without ice cover is wider than that with a rough ice cover.

Figure 5. Simulated soft output at the receiver in the waveguide with (right figure) and without rough ice cover (left figure) at the range of 5 km, I(t) is the in-phase component of a complex envelope, Q(t) is the quadrature component of a complex envelope.

The quality of transferred information is estimated by a bit error rate (BER). The values of BER are averaged over 10 independent realizations of transferred information. Underwater communication simulation at the range of 5 km shows that BER in the waveguide with and without ice cover is equal to 0.028±0.003 and 0.179±0.003, respectively. The confidence interval probability is 95 ?. We note that the obtained estimates are valid for a large signal-to-noise ratio when the bit error is associated with the physical properties of a shallow water waveguide only.

Acknowledgments
The work was supported by RFBR, 16-29-02036 and 16-32-60194.
References

[1] Freitag L, Koski P, Singh S, Maksym T, and Singh H 2017 Acoustic communications under shallow shore-fast Arctic ice. OCEANS 2017-Anchorage. IEEE pp 1-5.

[2] http://nsidc.org/data/G01360

[3] Katsnelson B, Petnov V, and Lynch J 2012 Fundamentals of shallow water acoustics. (Springer, New York, Dordrecht, Heidelberg, London).

[4] Kuryanov B F, Penkin M M 2010 Digital Acoustic Communication in Shallow-Water Sea for Oceanological Applications Acoustical Physics 56 (2) pp 218-227.

[5] Volkov M V, Grigoriev V A, Zhilin I V, Lunkov A A, Petnikov V G and Shatravin A V 2018 An Arctic-Type Shallow-Water Acoustic Waveguide as an Information Transmission Channel for Underwater Communications Acoustical Physics 64 (6) pp 692-697.