• far acoustic underwater communications, for which the focusing not only provides an advantageous signal/noise ratio at the reception point, but also ensures effective suppression of multipath reception [9];

• the acoustic tomography of shallow water, in which case the long-range reverberation can be suppressed owing to focusing [10, 11].

The authors' research results presented in this report were obtained with support from the RFBR (projects 08-02-00283, 10-02-01019, and 11-02-00779).

## References

1. Dargeiko M M et al. *Izv. Vyssh. Uchebn. Zaved. Radiofiz.* **27** 746 (1984) [*Radiophys. Quantum Electron.* **27** 516 (1984)]
2. Fink M et al. *Rep. Prog. Phys.* **63** 1933 (2000)
3. Zverev V A *Izbrannye Trudy* (Selected Works) (N. Novgorod: IPF RAN, 2004)
4. Kuperman W et al. *J. Acoust. Soc. Am.* **103** 25 (1998)
5. Zverev V A, Korotin P I, Stromkov A A *Akust. Zh.* **54** 69 (2008) [*Acoust. Phys.* **54** 58 (2008)]
6. Lunkov A A, Petnikov V G, Stromkov A A *Akust. Zh.* **56** 256 (2010) [*Acoust. Phys.* **56** 228 (2010)]
7. Kuz'kin V M et al. *Akust. Zh.* **52** 74 (2006) [*Acoust. Phys.* **52** 65 (2006)]
8. Kuz'kin V M, Pereselkov S A *Akust. Zh.* **53** 833 (2007) [*Acoust. Phys.* **53** 736 (2007)]
9. Edelmann G F et al. *IEEE J. Ocean. Eng.* **27** 602 (2002)
10. Kim S et al. *J. Acoust. Soc. Am.* **115** 1525 (2004)
11. Pereselkov S A, Petnikov V G *Akust. Zh.* **53** 400 (2007) [*Acoust. Phys.* **53** 348 (2007)]

PACS numbers: **43.20.+g**, **43.30.+m**, 43.60.Pt
DOI: 10.3367/UFNe.0181.201111l.1222

# Low-mode acoustics of shallow water waveguides

A G Luchinin, A I Khil'ko

## 1. Introduction

The industrial exploitation of gas and oil fields on the Arctic Shelf and in shallow marginal seas motivates creating information provision with hydroacoustic (HA) facilities aimed, among others, at the tasks of hydroacoustic communications and subsea surveillance. These tasks are usual for underwater acoustics, yet for a long time they were dealt with mainly at moderate distances (1–10 km), when utilizing high-frequency sound waves was efficient [1].

A new stage in the development of underwater acoustics was brought about by using low-frequency (LF) sound to ensure the solution of information tasks over large distances ($10^3$ km or more) in the deep sea. The research related to such HA systems was initiated abroad by W Munk and colleagues [2] in the 1970s. By the end of the 1970s, Soviet scientists, led by A V Gaponov-Grekhov, actively joined this research. During a short stretch of time they have contributed to the basic principles of LF underwater acoustics, created original low-frequency hydroacoustic (LFHA) transmitters, and carried out experiments in which diffracted LFHA signals have been measured in deep underwater HA channels over long observation distances on record [3].

By the end of 1980, prompted by the increasing interest in the industrial exploitation of the ocean shelf, the realization of HA-observations in extended regions of shallow seas became a pressing issue. In this case, the interaction of an HA field with the sea surface and bottom becomes essential, and, as a result, the field is strongly damped and loses coherence [4]. Moreover, the sound wave propagation is accompanied by high levels of reverberation noise [5]. These effects are the strongest for the interfering multimodal part of LFHA pulses which, as indicated by observations, is unstable in time and rapidly decays. Because of this, past endeavors relying on the usage of individual monopole sources for long-range LF sonar in shallow seas, the increase in their power, or the usage of large receiving arrays failed in providing the necessary progress to solve this problem.

## 2. The mode shadow and tomographic reconstruction of inhomogeneities

The idea of how to create information HA provision emerged in discussions among A V Gaponov-Grekhov, V I Talanov, V A Zverev, and V V Kovalenko in 1995–1996. Its essence reduces to utilizing only well-propagating LF waveguide (200–400 Hz) modes (in most cases they are also the lower-order modes) for acoustic background illumination of water depth in shallow seas and performing their selective detection. This approach was known in optics and radiophysics but has not been utilized in ocean acoustics.

As confirmed by estimates, such a low-mode-number field, owing to its relatively weak dissipation, should have a larger intensity than a multimode one, given the same energy delivered to the transmitting complex. Additionally, making use of low-mode HA fields could be advantageous in reducing reverberation as a whole and, in particular, the correlation noise from the direct illumination signal if one receives signals belonging to modes of other numbers (it is the shadow principle, also adapted from optics, but in this case applied to modes).

Subsequent analysis has shown that by using the complexly modulated mode pulses, matched to the waveguide, in HA observations in shallow seas it is possible not only to maintain long-distance underwater communications, but also to realize HA sonar through ultimate observation distances. In order to better resolve the underwater landscape over extended sea regions, the method of multistatic (tomographic) surveillance has been adopted, according to which the resultant object image is formed by accumulating projections.

Taking into account all the above-mentioned principles which define the concept of low-mode shallow-sea acoustics, the low-mode pulse acoustic tomography (LMPAT) method has been proposed. Its essence can be formulated as follows. With the help of a set of extended vertical arrays $S_i$ ($i = 1, \ldots, I$), pulse signals corresponding to a particular mode number $n$ are generated, with a sufficiently narrow uncertainty function in the 'frequency–time' parameter plane. The waveguide vertical profile and mode structure are assumed to be known.

Understandably, the excitation of an individual mode is impossible in practice because of the finiteness of the

**A G Luchinin, A I Khil'ko** Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, Russian Federation
E-mails: Luch@hydro.appl.sci-nnov.ru, A.khil@hydro.appl.sci-nnov.ru

*Uspekhi Fizicheskikh Nauk* **181** (11) 1222–1228 (2011)
DOI: 10.3367/UFNr.0181.201111l.1222
Translated by S D Danilov; edited by A Radzig

transmitting array aperture and the impossibility of placing sources deep into the ocean bottom. To synthesize a desired field distribution over the transmitting aperture, it is therefore necessary that all extra emitted modes stay substantially weaker than a single mode generated in a consistent way [6, 7]. In this case, the generated signal can be considered as a low-mode-number one. The pulses scattered by an observed inhomogeneity and corresponding to modes of numbers $m = 1, \ldots, M$, where $M$ is the total number of modes propagating in the waveguide, are detected with the help of extended vertical receiver arrays $R_j$ $(j = 1, \ldots, J)$. For each of the modes singled out by the receiver system, the matched filtering of pulses, spanning through time delays $\tau$ and Doppler frequency shifts $\Omega$, is performed. The number and position of sound sources and receiver systems, as well as the number of mode tomographic projections corresponding to each 'source–receiver system' pair, may vary.

As a result, signals registered for each pair of combinations of the transmitting and receiving arrays are the functions of several variables: the transmitted and detected mode numbers, and of time delays and Doppler frequency shifts.

By jointly processing all spatial mode and frequency tomographic projections, one retrieves spatial and temporal parameters of the observed inhomogeneities. Far from the source, the field in HA waveguides is given by a finite sum of $N$ propagating modes (for a horizontally homogeneous waveguide, the numbers of modes at the locations of the source and receiver coincide and $N \equiv M$). A mode is characterized by its eigenfunction $\varphi_n(z)$ and complex-valued eigenvalue $h_n(\omega)$, whose imaginary part is determined by the mode decay decrement $\delta_n(\omega)$. Each $i$th source of the tomographic system, being an array of transducers of length $L_i$, emits a sequence of narrow-band sounding pulses $f_0(t)$ with spectrum $F(\omega - \omega_0)$, where $\omega_0$ is the carrier frequency. If the location depths and sizes of sound source arrays are selected in an optimal way, the emitted low-mode signal will contain an emitted mode with number $n$, whose amplitude maximally exceeds the amplitudes of all other modes [6]. In this case, under the assumption that the intermode dispersion effects are small (this imposes limitations on the bandwidth of emitted pulses, and also on the distances through which they are observed), the direct (unscattered) pulse signal from the $j$th receiving array of length $L_j$ can be written, after matched filtering, in the following form

$$
\begin{aligned}
&{}^0P_{ij}^{nm}(r_{ij}, \tau_{ij}^{nm}, \Omega_{ij}^{nm}) \\
&= A_n^i A_n^j \exp\left[\mathrm{i}\left(h_n r_{ij} - \frac{\pi}{4}\right)\right](h_n r_{ij})^{-1/2} F_{\mathrm{ind}}(\tau_{ij}^{nn}, \Omega_{ij}^{nn}) \\
&+ \sum_{\substack{\eta \neq n \\ \mu \neq m}}^{M} A_\eta^i A_\mu^j \exp\left[\mathrm{i}\left(h_\eta r_{ij} - \frac{\pi}{4}\right)\right](h_\eta r_{ij})^{-1/2} F_{\mathrm{ind}}(\tau_{ij}^{\eta\mu}, \Omega_{ij}^{\eta\mu}) , \quad (1)
\end{aligned}
$$

where $h_n = h_n(\omega_0)$; $\tau_{ij}^{nm} = r_{ij}/v_n(\omega_0)$ is the delay in the pulse pertaining to the $n$th mode in the receiving channel which corresponds to the mode with number $m$; $v_n(\omega_0)$ is the group velocity of mode $n$; $\Omega_{ij}^{nm}$ is the Doppler frequency shift caused by the motion of the scattering object; $A_{n,m}^{i,j} = \int_0^{L_{i,j}} g_{n,m}^{i,j}(z)\, \varphi_{n,m}(z)\, \mathrm{d}z$ are the mode excitation coefficients for the transmitting and receiving arrays, respectively; $g_{n,m}^{i,j}(z)$ are optimal weight factors along array apertures [8], and $F_{\mathrm{ind}}(\tau, \Omega)$ is the uncertainty function of the sounding pulses:

$$
F_{\mathrm{ind}}(\tau, \Omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \mathrm{d}\omega\, F(\omega)\, F_0(\omega - \Omega) \exp\left[\mathrm{i}(\omega - \Omega)\tau\right] ,
$$

where $F_0(\omega)$ is the spectrum of the sounding signal replica.

Given ideal spatial filtering, which is not achievable under natural conditions, for which mode orthogonality conditions hold at array apertures, the second term in the form of a sum of small-amplitude interfering modes disappears on the right-hand side of Eqn (1), leaving only the first term related to the field of acoustic illumination for a single emitted mode.

In observations, one detects sounding pulses that experience diffraction by waveguide inhomogeneities. In the framework of the mode-guided description, the complex-valued amplitudes of diffracted waveguide modes are determined by the scattering matrix which depends on the internal structure, shape, and location of inhomogeneities [5–7]. Given the acoustic illumination of inhomogeneities by a pulse signal of the $n$th mode, the amplitude of each pulse of the diffracted mode with index $m$ will be formed through contributions of the signals scattered on all inhomogeneities confined within the respective pulse volume, the points of which, $r'$, satisfy the condition $|t - r_{1i} v_n^{-1} + r_{2j} v_m^{-1}| < \Delta\tau/2$, where $r_{1i} = |r_i - r'|$ and $r_{2j} = |r' - r_j|$ are the distances from the scatterer to the source and receiver, respectively. Generally, the observed inhomogeneities move, so that the scattered pulses experience the Doppler frequency shift.

For the narrow-band pulses of acoustic illumination considered here, and given the fairly small scatterer displacement velocities $V_{\mathrm{s}}$, all scatterers satisfying the condition

$$
\left|\omega_0 V_{\mathrm{s}}(r')\left(v_n^{-1} \cos\alpha_i(r_i, r') - v_m^{-1} \cos\beta_j(r_j, r')\right)\right| < \Delta\Omega
$$

will fall into the separate channel along the Doppler shift-axis. Here, $\alpha_i(r_i, r')$ and $\beta_j(r_j, r')$ are, respectively, the angles between the direction of displacement velocity vector of an elementary scatterer at point $r'$ and radius vectors drawn from the location point of the scatterer to the source and the receiving system. The quantities $\Delta\tau$ and $\Delta\Omega$ are determined by the width of the uncertainty function $F_{\mathrm{ind}}(\tau, \Omega)$ of sounding pulses along the time delay- and Doppler frequency shift-axes, respectively.

When performing digital signal processing, in each of 'time delay–Doppler frequency shift' planes related to the pair of the emitted mode with number $n$ and the received one with the number $m$, it is possible to introduce for each source–receiver pair $(i, j)$ the set of channels corresponding to the intervals of time delays ${}^0t_{ij}^{nm} + (l-1)\Delta\tau < \tau_{ij}^{nm} < {}^0t_{ij}^{nm} + l\Delta\tau$ and Doppler frequency shifts $(k \mp 1)\Delta\Omega < \Omega_{ij}^{nm} < k\Delta\Omega$, where $l = 1, 2, \ldots, L$ and $k = \pm 1, 2, \ldots, \pm K$ are the channel numbers, and ${}^0t_{ij}^{nm}$ are the initial values of time delays fixed for each of the tomographic projections $(i, j, n, m)$.

After signal processing, which consists in a matched filtering of the received mode pulses, we will generally have, adopting the discretization defined above, $I \times J \times N \times M \times K \times L$ tomographic projections, the signals of which carry integral characteristics of all inhomogeneities confined within pulse volumes for each of the projections. The joint processing of signals related to these projections provides the reconstruction of differential characteristics of the observed inhomogeneities, i.e., the distribution of their parameters over the observation domain. Under the assumption that multiple scattering effects are negligible, the amplitudes of modes scattered by separate elements of the pulse volume are defined by the components of the inhomogeneity spatial spectrum, satisfying the resonance scattering condition $\mathbf{k}_{ij}^{nm} = h_n \mathbf{r}_{1i}/r_{1i} - h_m \mathbf{r}_{2j}/r_{2j}$.

The observed amplitudes of the acoustic field pressure will represent the sum of the acoustic illumination field ${}^0p_{ij}^{nm}$, the field components ${}^\sigma p_{ij}^{nm}$ and ${}^R p_{ij}^{nm}$ diffracted by the observed inhomogeneity and scattered by all interfering inhomogeneities, respectively, and also of the ocean additive noise source field ${}^N p_j^m$. In a general case, each component of the received signal should be considered as a random signal with certain inherent statistical properties.

Assuming the interference effects are small, to assess the received signal intensity, averaging is performed over statistical ensembles of respective random inhomogeneities and noises. If the random inhomogeneities are relatively mild or the length of tomographic paths is moderate, the acoustic illumination field can approximately be considered coherent. For the illumination with acoustic mode $n$, the intensities of signal components at the output of the matched filter, pertaining to the pulses of the $m$th received mode, which are diffracted by both the observed (with index $\sigma$) and interfering (with index $R$) inhomogeneities, are defined by the mode scattering matrix [5–7]:

$$\begin{aligned}
&\left({}^{\sigma,R}I_{nm}^{\nu\mu}\right)_{ij}(\tau_{ij}^{nm}, \tau_{ij}^{\nu\mu}, \Omega_{ij}^{nm}, \Omega_{ij}^{\nu\mu}) \\
&\simeq \frac{8}{\pi h_0^2}\int_{-\infty}^{\infty} \frac{1}{r_{1i}\, r_{2j}} \exp\left[\mathrm{i}(h_\nu - h_n) r_{1i} + \mathrm{i}(h_\mu - h_m) r_{2j}\right] \\
&\times \int_{-\infty}^{\infty} {}^{\sigma,R}W_{nm}^{\nu\mu}\left(\frac{h_\nu + h_n}{2}\frac{\mathbf{r}_{1i}}{r_{1i}} - \frac{h_\mu + h_m}{2}\frac{\mathbf{r}_{2j}}{r_{2j}}\,;\,\omega', r'\right) \\
&\times F_{\mathrm{ind}}\left(\tau_{ij}^{nm} - \frac{r_{1i}}{v_n} - \frac{r_{2j}}{v_m}\,;\,\omega' - \Omega_{ij}^{nm}\right) \\
&\times F_{\mathrm{ind}}^{*}\left(\tau_{ij}^{\nu\mu} - \frac{r_{1i}}{v_\nu} - \frac{r_{2j}}{v_\mu}\,;\,\omega' - \Omega_{ij}^{\nu\mu}\right) \mathrm{d}\omega'\, \mathrm{d}^2 r', \qquad (2)
\end{aligned}$$

where $h_0$ is the wave number on the channel axis for the carrier frequency, and ${}^{\sigma,R}W_{nm}^{\nu\mu}(\mathbf{k}, \omega, r)$ are the appropriate components of the local spectrum of the inhomogeneity correlation function with respect to the difference variables for the sum of surface, bottom, volume, and spatially localized inhomogeneities. Integration in formula (2) is performed over the horizontal coordinates, and the location depth of inhomogeneities is taken into account in computations of the components of the local inhomogeneity spectrum [6, 7].

## 3. Imitating model for the adaptation to observational conditions

A tomographic reconstruction of the object image consists in estimating the values of observed parameters of a model describing the object. For a spatially localized inhomogeneity, in particular, its coordinates and shape, together with the velocity and displacement direction, may serve as the observable parameters. When wind waves constitute the object of observation, the speed and direction of the wind generating them can be among the measured parameters [5, 6].

Let us denote by the $\mathbf{p}$ vector a set of observable model parameters. The values of the $\mathbf{p}$ components are estimated by the method of statistical hypothesis testing. These hypotheses are defined by the solution of the direct diffraction problem based on *a priori* information in the form of models of the medium, the object under observation, the levels of disturbances and noises, and a model describing the configuration of the observation system. The solution corresponds to the global minimum of the residual between the vectors $\mathbf{q}$ of measured parameters and vectors $\mathbf{q}^{(\mathbf{p})}$ which correspond to the hypotheses being exhausted, for example, in the form of the $Lp$-norm:

$$\Psi(\mathbf{p}) \equiv \|\mathbf{q} - \mathbf{q}^{(\mathbf{p})}\|^{\eta} \to \min_{\mathbf{p}} \Psi(\mathbf{p}).$$

The rule for taking the decision that the hypothesis for the value of vector $\mathbf{q} = \mathbf{q}^{(\mathbf{p})}$ is valid is commonly written out as $\|\mathbf{q} - \mathbf{q}^{(\mathbf{p})}\|^{\eta} < \sigma$, where the norm $\|\,.\,\|$, the exponent $\eta$, and the threshold values of $\sigma$ are defined in a general case by the distribution function of the probability density of the vector of measured parameters, by the given magnitudes of the probabilities of the first- and second-order errors in taking decisions, noises, disturbances, and other factors.

The formulation and testing of hypotheses for the parameters of the object (notably, on its location in the observation domain) assume the assessment of optimal space–frequency aperture distributions [8], relevant statistics, and criteria for each tomographic projection, which are adapted to the sounding conditions. Additionally, one needs to design optimal algorithms for accumulating projections and suggest the trajectory of the solution search (hypotheses exhaustion).

To solve these tasks, an imitating computer model has been developed. It relies on oceanographic databases, physical models concerning the formation of signals and disturbances, and algorithms of partially coherent accumulation and decision-making. It is a program-algorithm complex equipped with an interactive interface [6–10]. The results of computations are presented as the observation probability distributions for the prescribed probabilities of false alarms in a given shallow sea region, depending on observation conditions (wind, currents, navigation noises, and so on).

An example of the analysis of potentialities offered by low-mode acoustics in a shallow sea is offered by simulations of a system composed of three receiver–transmitter (RT) arrays used to trace an iceberg. The arrays are located at the vertices of an equilateral triangle with a side of 100 km (the RT modules are marked by dark points in Fig. 1a). The carrier frequency of the sounding narrow-band pulses was selected to be 200 Hz. If certain observed components of the parameter vector, in particular, the iceberg speed and drift direction, are fixed, the observation reduces to estimating the iceberg location. It has been assumed in the analysis that the iceberg moves at a speed of 1.5 m $\mathrm{s}^{-1}$ along a set of trajectories, each making an angle of $\pi/4$ with the $x$-axis (Fig. 1a). The level of additive noise was taken to be 70 dB relative to 1 $\mu$Pa. The power of the acoustic illumination source was selected equal to 100 W. As follows from simulation results displayed in Fig. 1b, the system's field of view is nonisoplanatic and substantially depends on observation conditions, such as the level and structure of noise and disturbances, the waveguide structure, and the motion parameters of the inhomogeneity observed. As follows from the numerical analysis, most frequently the outer boundary of the visual field is determined by additive noises, whereas the reverberation disturbance from random waveguide inhomogeneities gives rise to the inhomogeneity of the field of view in the form of regions with poor visibility.

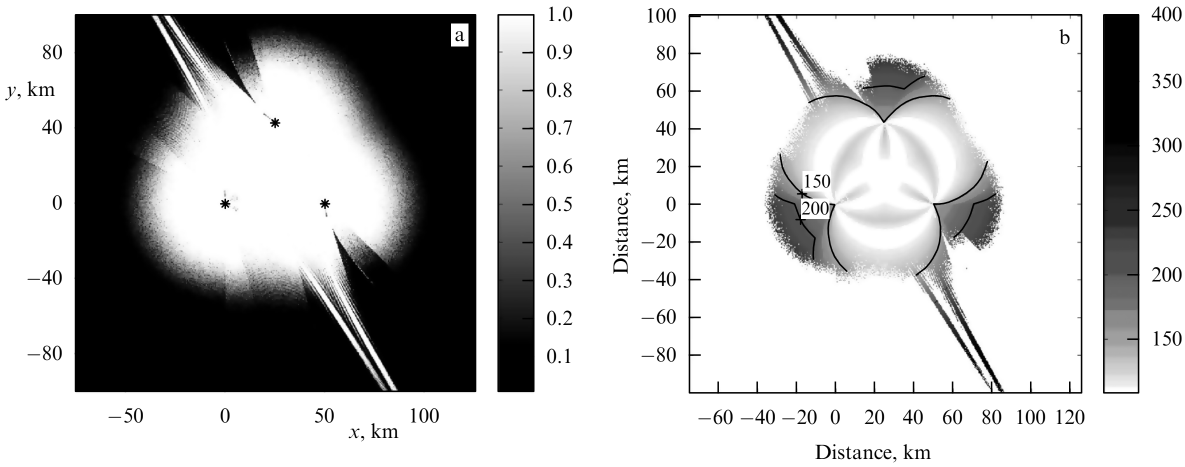


**Figure 1.** (a) Total field of view in the horizontal plane in the case of exciting ten mode and nine spatial projections for the noise level of 82 dB. (b) The distribution of spatial resolution values (corresponding to panel a) for the excitation of the first mode and detection of the third one. The brightness scale and spatial resolution values alongside the isolines are given in meters.

The shape of the visual field can noticeably change as a consequence of changes in the velocity and motion trajectory of the observed inhomogeneity and in the parameters of surface wind-generated waves. Notably, if the iceberg drifts along the track of bistatic observations, the regions where the bottom reverberation hampers observations will be located at right angles to the source–receiver line.

As confirmed by numerical simulations, the multistatic low-mode observation system is not limited solely to observations of spatially localized inhomogeneities, but can also tackle randomly distributed inhomogeneities, such as wind waves, and also the HA waveguide characteristics [6, 7, 9]. The results mentioned above, together with those from other studies, indicate that the ocean mode acoustics assures observations within extended zones with a minimum number of RT modules and minimum requirements imposed on the power supply.

## 4. Marine experiments on low-mode acoustics of shallow seas

Numerical simulations were instrumental in shaping the optimal design of a low-mode acoustic system for specific shallow-sea regions and developing the procedure of marine tests. To carry out experiments, original transmitting and receiving complexes have been designed under the supervision of B N Bogolyubov and P I Korotin. They incorporate vertically oriented transmitting and receiving LFHA arrays. In particular, by employing light and compact effective electromagnetic LF transmitters, a 16-element array with an adaptive-control system has been constructed (Fig. 2). Furthermore, unique receiving LFHA complexes have been designed, comprising hundred-meter arrays of digital hydrophones boosting a broad dynamic range and capable of working autonomously up to 7 days [6, 7]. The array aperture distributions were selected adaptively so that they conform to the array configuration which varies because of wind waves and drift, and to the hydrology. For the transmitting array, a special iterative algorithm was developed. It ensured real-time formation of mode pulses of acoustic illumination matched with the HA waveguide, with due regard for compensation of the interaction between the transmitters through the ambient medium [6, 7, 11, 12].

**Figure 2.** Deployment of a 16-element transmitting complex to its underwater position from the deck of the research vessel.

A set of experiments was carried out in marine conditions after creating an appropriate equipment and developing measurement procedures. They were aimed at tests of the realizability and efficiency of low-mode shallow-sea acoustics. Their outcome was, first, the demonstration of the operating capacity of equipment and the possibility of compensation of interactions among the transmitters as they emit and receive low-mode pulses (Fig. 3). The level of energy concentration for the waveguide-matched generation of the low-mode field in experiments proved to be close to the calculated one (7–10 dB). The agreement with predictions was also manifested through an essential decrease in the transition distance for arrays, compared to that for a single transmitter (Fig. 3b). Additionally, the low-mode field appeared to be much more stable in time (15–30 min) than the field due to a single source (Fig. 4).

The high coherence of signals was demonstrated by detecting low-mode pulses at large distances (in excess of 100 km). Such a peculiarity facilitated their coherent, waveguide-matched accumulation over space and frequency in the 10–20-Hz band for apertures spanning more than 1 km. Experimental demonstrations have also revealed a substan-

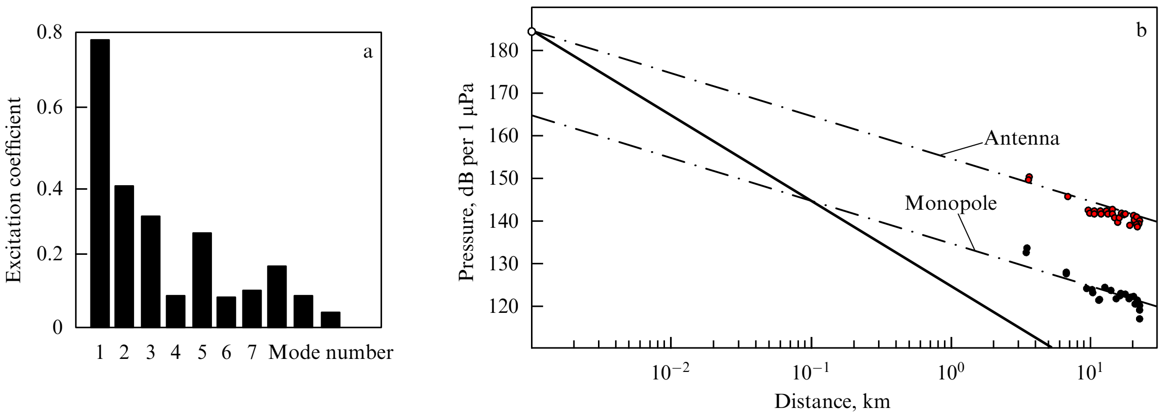


**Figure 3.** (a) The mode signal spectrum detected with a homogeneous amplitude–phase distribution at a distance of 10 km from the emitting array which spans the location depth range from 44 to 89 m. (b) The signal level versus distance for an emitting antenna and a monopole. The dashed-dot lines correspond to the cylindrical law of a signal level decay, and the solid line fits the spherical law. The circle on the ordinate axis marks the level of the transmitted signal which is the same for a single monopole and for an array of emitters.

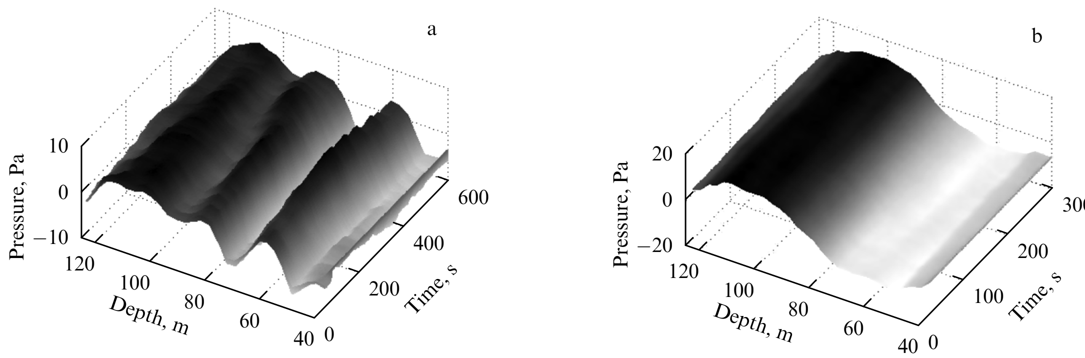


**Figure 4.** Sound field distribution over depth versus time, as produced by a single emitting monopole in an antenna (a), and by an antenna with a homogeneous amplitude-phase distribution over its aperture (b). The observation distance is 4 km.

tial reduction in the levels of surface and bottom reverberation (more than by 10–15 dB) with respect to the case of a single transmitter and multiple modes (Fig. 5). It was also experimentally established that the main sources of LFHA noise are distant storms and navigation — concerning low-mode-number fields — and wind-generated waves affecting more those modes with larger numbers. It was shown both in simulations and experiments that the reduction in the size of arrays leads to an essential (more than a few orders of magnitude) decrease in the area of a zone of consistent observations [6–9].

## 5. Conclusions

As a result, the research work described here laid the foundations of a new technology offering effective multistatic observations in shallow seas. This technology can be considered as the basis for applications in Russian shelf seas, in particular, on the Arctic Shelf. The further advancement of this technology is linked to the potential of its usage as a component in autonomous or deployed receiving–transmitting modules and elements of underwater acoustic communications. Also of importance is the research aimed at the design of adaptive observation algorithms relying on cognitive methods.

Two fields of fundamental and applied research are of key significance for the further development and practical implementation of low-mode acoustic methods. The first involves the design and construction of new, more efficient, light and compact LFHA transmitting systems. This area envisages the search for new materials and generation principles of LFHA fields. The second key area is, in our opinion, the elaboration of methods and algorithms for adaptive automated control of the potential inherent in the observation system. The main idea here is physical and technological principles needed for creating a control system that will provide automated generation of hypotheses by the imitating system in the course of observations, with allowance made for hydroacoustical conditions.

The aforementioned critical technologies offer solutions to a set of fundamental scientific problems occurring in studies of shallow regions of the world's oceans. These technologies can also be utilized in adjacent branches of science. An example is furnished by coherent seismoacoustic profiling used in searching for natural resources on the ocean bottom. In this case, one applies highly coherent LFHA transmitters, which ensures that the accumulation over space and frequencies of bottom-reflected signals is coherent and matches the ambient medium. This helps achieve a unique efficiency in reconstruction of deeply located bottom inhomogeneities, while conforming the requirements imposed by ecological security of HA sounding [13].

**Acknowledgments.** This work was supported through the program of the Presidium of the RAS, 'Fundamental

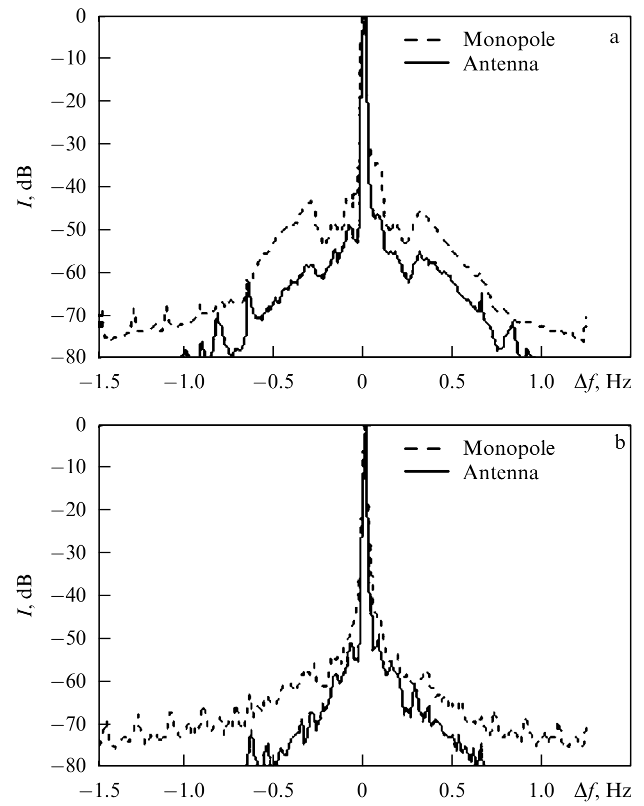


**Figure 5.** Spectra of intensity $I$ of a signal generated by a monopole and an array of transmitters, which is scattered by surface wind-generated waves, at a distance of 10 km: (a) the spectrum of the total signal at the antenna, and (b) the spectrum of the first waveguide mode.

problems in oceanography: geology, physics, biology, ecology'; the program of the Physical Sciences Division of the RAS, 'Fundamental principles of acoustical sounding of artificial and natural media'; the Federal Targeted Program, 'Scientific and scientific-pedagogical personnel of innovative Russia' (contract 02.740.11.0565), and RFBR (project 09-02-00044).

## References

1. Urick R J *Principles of Underwater Sound* (New York: McGraw-Hill, 1975) [Translated into Russian (Leningrad: Sudostroenie, 1978)]
2. Munk W, Worcester P, Wunsch C *Ocean Acoustic Tomography* (Cambridge: Cambridge Univ. Press, 1995)
3. Abrosimov D I et al. *Dokl. Akad. Nauk SSSR* **299** 477 (1988) [*Sov. Phys. Dokl.* **33** 123 (1988)]
4. Katsnelson B G, Petnikov V G *Akustika Melkogo Morya* (Shallow Water Acoustics) (Moscow: Nauka, 1997) [Translated into English (London: Springer, 2002)]
5. Goncharov V V et al. *Akusticheskaya Tomografiya Okeana* (Acoustic Tomography of Ocean) (N. Novgorod: IPF RAN, 1997)
6. Luchinin A G, Khil'ko A I *Akust. Zh.* **51** 228 (2005) [*Acoust. Phys.* **51** 182 (2005)]
7. Khil'ko A I et al. *Akust. Zh.* **53** 437 (2007) [*Acoust. Phys.* **53** 381 (2007)]
8. Smirnov I P, Khil'ko A I, Romanova T V *Izv. Vyssh. Uchebn. Zaved. Radiofiz.* **51** 50 (2008) [*Radiophys. Quantum Electron.* **51** 45 (2008)]
9. Khil'ko A I et al., in *Akusticheskie Izmereniya i Standartizatsiya. Ul'trazvuk i Ul'trazvukovye Tekhnologii. Atmosfernaya Akustika. Akustika Okeana. Sbornik Trudov XXII Sessii Rossiiskogo Akusticheskogo Obshchestva i Sessii Nauchnogo Soveta po Akustike RAN* (Acoustic Measurements and Standardization. Ultrasound and Ultrasonic Technologies. Atmospheric Acoustics. Ocean Acoustics. Collection of Papers of the XXIIth Session of the Russian Acoustical Society and Scientific Council on Acoustics, RAS) Vol. 2 (Moscow: GEOS, 2010) p. 244
10. Raevsky M A, Khil'ko A I *Izv. Vyssh. Uchebn. Zaved. Radiofiz.* **50** 20 (2007) [*Radiophys. Quantum Electron.* **50** 18 (2007)]
11. Averbakh V S et al. "Ob upravlenii gruppoi vzaimodeistvuyushchikh akusticheskikh monopolei" ("On the control of the group of interacting acoustic monopoles") Preprint No. 190 (Gor'ky: IPF AN SSSR, 1988)
12. Smirnov I P, Smirnova I R, Khil'ko A I *Akust. Zh.* **56** 813 (2010) [*Acoust. Phys.* **56** 1067 (2010)]
13. Lazarev V A et al., in *Fizicheskie, Geologicheskie i Biologicheskie Issledovaniya Okeanov i Morei* (Physical, Geological, and Biological Studies of Oceans and Seas) (Exec. Ed. S M Shapovalov) (Moscow: Nauchnyi Mir, 2010) p. 300

PACS numbers: **43.25.+y**, **43.30.+m**, 87.50.Y
DOI: 10.3367/UFNe.0181.201111m.1228

# Developments in physical acoustics 2010: a review of materials from the Scientific Council on Acoustics of the Russian Academy of Sciences

I B Esipov

One of the tasks of the Scientific Council on Acoustics, RAS is to inform the scientific community of the most interesting results obtained in investigations performed in laboratories of the Russian Academy of Sciences and leading universities and research institutions in Russia. The Council comprises a number of sections discussing the development of investigations in the following fields:

(i) *ocean acoustics* (A G Luchinin, Head, Institute of Applied Physics, RAS);

(ii) *geoacoustics* (A V Nikolaev, Head, Shmidt Institute of Earth Physics, RAS);

(iii) *aeroacoustics* (V F Kop'ev, Head, Central Aerohydrodynamic Institute);

(iv) *vibroacoustics* (Yu I Bobrovnitskii, Head, Blagonravov Institute of Machine Science, RAS);

(v) *physical acoustics of solids and acoustoelectronics* (I E Kuznetsova, Head, Saratov Division, Kotel'nikov Institute of Radioengineering and Electronics, RAS);

(vi) *physical ultrasound* (O A Sapozhnikov, Head, Physics Department, Lomonosov Moscow State University).

As follows from the topics of these sections, the Scientific Council focuses on studies in the field of physical acoustics and its applications in related fields, such as Earth and engineering sciences.

The research activity of the Scientific Council on Acoustics, RAS in 2010 was summarized at two sessions held at the Prokhorov General Physics Institute (GPI RAS) and at the Kotel'nikov Institute of Radioengineering and Electronics (IRE), RAS in November and December 2010,

**I B Esipov** Gubkin Russian Petroleum and Gas University, Moscow, Russian Federation, and the Andreev Acoustic Institute, Moscow, Russian Federation. E-mail: igor.esipov@mail.ru

*Uspekhi Fizicheskikh Nauk* **181** (11) 1228 – 1234 (2011)
DOI: 10.3367/UFNr.0181.201111m.1228
Translated by M N Sapozhnikov; edited by A Radzig