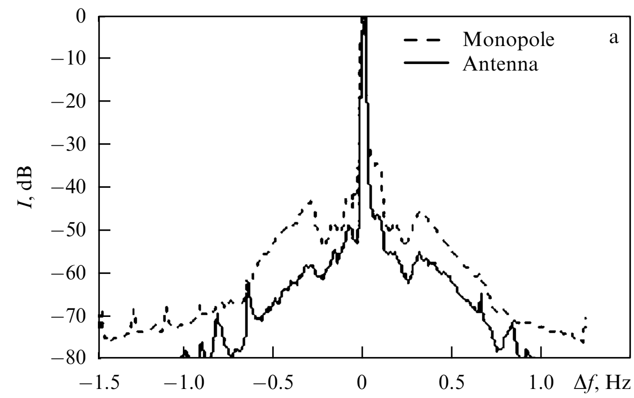

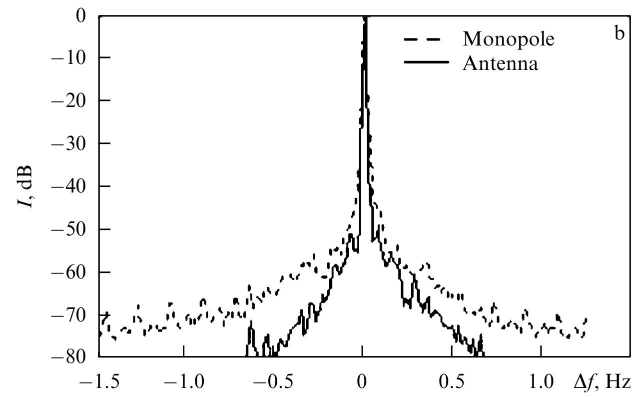

Figure 5. Spectra of intensity I of a signal generated by a monopole and an array of transmitters, which is scattered by surface wind-generated waves, at a distance of 10 km: (a) the spectrum of the total signal at the antenna, and (b) the spectrum of the first waveguide mode.

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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

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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,

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respectively. The most important achievements in 2010 pointed out at these sessions are discussed below. These achievements include:

(i) a new phenomenon of explosive instability and spatial localization of ultrasonic waves in ferromagnets;

(ii) an original method for metrology of nonlinear fields of ultrasonic focusing radiators in biological tissue;

(iii) experimental demonstration of the efficiency of coherent methods for the seismoacoustic sounding of the sea bottom.

In addition, it is important to highlight the development of a pilot parametric acoustic antenna for long-path ocean studies. The antenna was deployed in 2010, and now the first results of testing this new nonlinear acoustic device have been obtained.

Consider each of these results in more detail. The phenomenon of *the explosive instability of ultrasound in magnetics* has been demonstrated and studied by V L Preobrazhensky and coworkers at the International Laboratory of Nonlinear Magnetoacoustics of Condensed Media affiliated with the Scientific Center of Wave Studies, GPI RAS [1, 2].

The interaction of acoustic (elastic) vibrations with a nonlinear magnetic structure establishes conditions for the observation of strongly nonlinear acoustic phenomena in a solid. The specific features of nonlinear magnetoacoustic interaction in magnetics have been investigated for many years at Preobrazhensky's laboratory. The fact is that the coupling coefficient between magnetic and acoustic fields for certain types of acoustic vibrations in a number of magnetically ordered materials reaches a few dozen percent. In this case, the magnetic contribution to anharmonic (nonlinear) elastic moduli can be $\Delta C^{(3)} \approx (10^3 - 10^4) C^{(2)}$, where $C^{(2)}$ is the second-order elastic modulus. Such a strong effective anharmonicity, considerably exceeding the intrinsic anharmonicity of a crystalline lattice, was called the giant anharmonicity [3]. Under such conditions, higher-order nonlinear effects are distinctly manifested. In this case, the introduced nonlinearity strongly depends on an external magnetic field.

The modulation of the third-order nonlinearity by an alternate magnetic field can provide efficient three-phonon parametric excitation. The above-threshold dynamics of phonon triads qualitatively differs from the parametric generation of phonon pairs in magnetic media studied earlier, which was manifested, in particular, in the phase conjugation of ultrasound with giant amplification [4, 5]. Theoretical studies and numerical simulations have shown that the above-threshold three-phonon interaction with the electromagnetic pump field in magnetically ordered media is accompanied by the development of explosive instability and the spatial localization of ultrasonic waves. Figure 1 demonstrates the results of numerical simulations of the explosive amplification of a traveling wave in an antiferromagnet [6]. Explosive instability was observed in experiments upon the excitation of α-Fe_2O_3 [1] and $FeBO_3$ [2] antiferromagnetic single crystals by two successive electromagnetic pulses. The first pulse, with the harmonic carrier corresponding to the natural frequency of the crystal, produced initial acoustic perturbations. Then, a pump pulse at the tripled frequency followed. The phase of this pulse was changed according to the law providing a singular increase in the intensity of elastic ultrasonic vibrations [1]. Experimental results presented in Fig. 2 show that the special phase modulation of the electromagnetic pump leads to the suppression of the phase

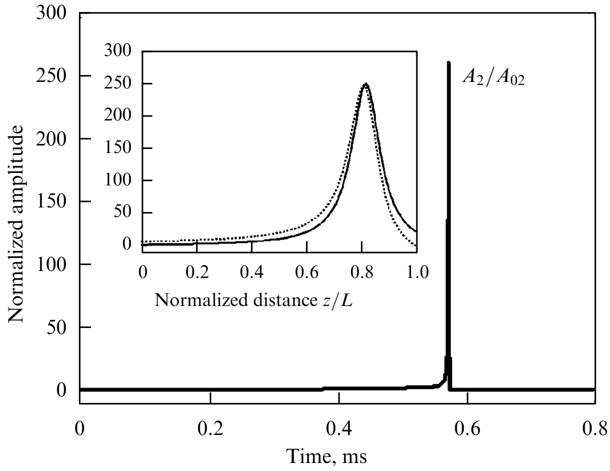

Figure 1. Time evolution of the explosive amplification of a traveling wave in a three-photon parametric process. The inset shows the spatial localization of the interacting waves. The solid curve corresponds to forward waves, and the dotted curve defines the backward wave.

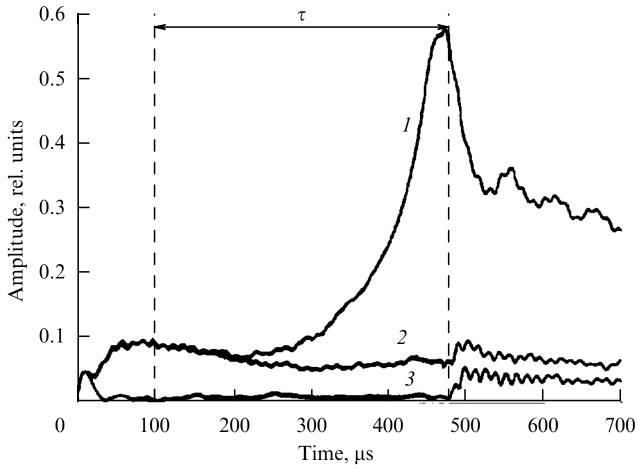

Figure 2. Experimental time dependence of the amplitude of magnetoacoustic vibrations at frequency ω upon transverse pumping of an α-Fe_2O_3 crystal by electromagnetic radiation at frequency 3ω with phase modulation of the pump (curve *1*), in the absence of pump modulation (curve *2*), and in the absence of the initial acoustic perturbation (curve *3*); τ is the pump pulse duration [5].

mechanism of nonlinear restriction of the amplitude of generated waves, and establishes conditions for the explosive above-threshold dynamics of three-phonon excitations.

Among the most important results obtained in the field of physical ultrasound, investigations of processes of *high-intensity focused ultrasound* (HIFU) were pointed out in connection with the possibility of their applications in noninvasive surgery. The results in this field were obtained at the Chair of Acoustics, Physics Department at Moscow State University.

The use of HIFU for the local heating and destruction of tissue without the usual surgical invasion and the damage of surrounding tissues is a rapidly developing medical technology [7]. The destruction of tissue irradiated by HIFU is caused by the absorption of the ultrasonic energy in the tissue, resulting in its heating, followed by the necrosis of cells inside the irradiated tissue volume. Thermal effects are often accompanied by mechanical damage to the tissue, which is caused by bubbles produced under the effect of ultrasound. Recently, interest in the use of new procedures for the mechanical destruction (emulsification) of tissues without thermal coagulation has been increasing.

The Chair of Acoustics in the Physics Department at Moscow State University is a leading Russian scientific center in the field of studies of physical processes initiated by high-power focused ultrasound in biological tissues. Investigations in this area are performed in close collaboration with other institutions and laboratories in Russia, the main therapeutic-ultrasound scientific centers in the USA and Europe, the manufacturers of HIFU equipment, and metrological institutes in different countries.

One of the important areas in the development of HIFU technologies is the use of nonlinear acoustic phenomena for increasing the efficiency of thermal action on tissues and producing new nonthermal biological effects. The radiation intensity at the focus of HIFU sources reached a few dozen kilowatts per cm^2, nonlinear effects leading to the formation of shock fronts (discontinuities) in the wave profile with amplitudes of up to 60–100 MPa. It is well known that the energy absorption of a nonlinear acoustic wave containing discontinuities principally differs from the energy absorption of harmonic waves. The energy absorption of a harmonic wave is proportional to the square of its amplitude, whereas the absorption of a discontinuous wave is proportional to the cube of the discontinuity amplitude. As a result, the efficiency of heating a medium by discontinuous waves can increase by a few dozen and even hundreds of times. In addition, shock waves are focused on a smaller volume, thereby increasing the action locality. HIFU irradiation in the discontinuous-wave mode produces rapid localized tissue heating and boiling for a few milliseconds, opening new possibilities for the development of HIFU technologies [8, 9].

Researchers at Moscow State University have proposed the control of nonlinear effects by utilizing the repetitively pulsed operation mode of HIFU radiators with the same time-averaged intensity, but different peak pressures and period-to-pulse duration ratios [9]. It has been shown in experiments performed in collaboration with the Center of Industrial and Medical Ultrasound (CIMU APL) in Seattle that this method can provide principally different actions in tissues [9]. Thus, during continuous irradiation of liver tissue by ultrasonic waves with a small initial amplitude (Fig. 3a), the wave at the focus is harmonic and produces a small thermal necrosis locus which is clearly observed in the tissue section in the focal plane (white region). As the initial wave amplitude is increased (Fig. 3b), the wave shape at the focus is distorted and the heating efficiency enhances, which can lead to an unexpected radically new effect of the acoustic action on biological tissue. It was found that if a tissue boils periodically at the end of each pulse, a purely mechanical destruction (emulsification) of the tissue without thermal necrosis becomes possible (Fig. 3b). Finally, if the initial-wave and discontinuity amplitudes at the focus are very large and boiling occurs for a longer time during each of the pulses, the damage is observed in the form of a cavity surrounded by a thermal necrosis zone (Fig. 3c). Thus, ultrasonic waves with the same average intensities can produce tissue damage with different morphologies and sizes.

It should be noted that until recently just the time-averaged radiation intensity was employed as the main characteristic of HIFU irradiation. The results presented

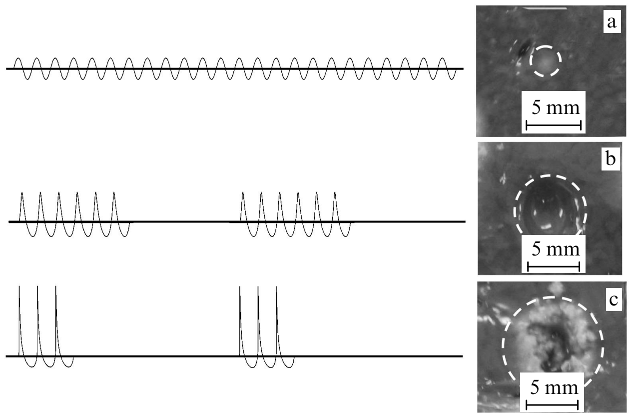

Figure 3. Profiles of an ultrasonic wave at the focus of an HIFU source and the corresponding types of tissue damage caused by repetitively pulsed HIFU irradiation.

above reveal that, to predict adequately the expected effects, a considerably greater number of parameters of the ultrasonic field are required. New methods in the metrology of ultrasonic fields produced by HIFU radiators [10], which were developed by researchers at the Chair of Acoustics in collaboration with the Center of Industrial and Medical Ultrasound in Seattle, and measurements of the parameters of a nonlinear field in biological tissues from experimental data or simulations in water [11] were used by the International Electrotechnical Commission in the development of the first International Ultrasonic Standard in surgery.

An interesting HIFU application concerns the development of irradiation methods in which acoustic obstacles are located between a radiator and the focus. These obstacles are first and foremost bones, in particular, thoracic bones which complicate the fulfillment of ultrasonic surgical operations, for example, on the liver or heart (Fig. 4). The presence of strongly reflecting or strongly absorbing acoustic obstacles in organism tissue significantly restricts more widespread clinical HIFU applications. The absorption of ultrasound in

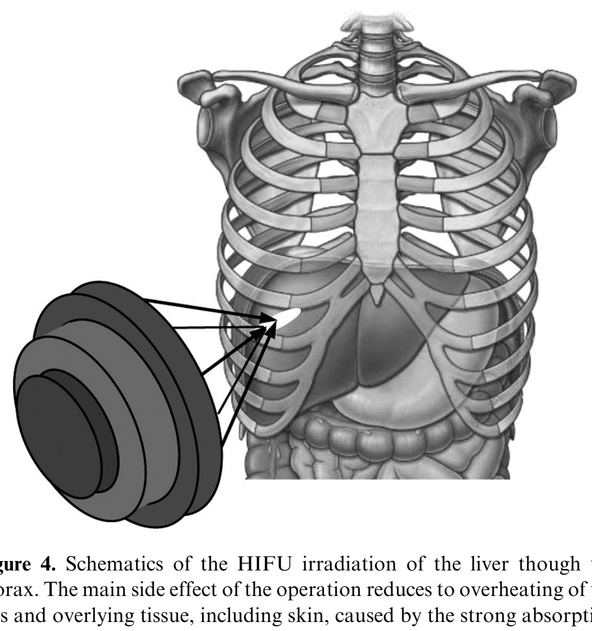

Figure 4. Schematics of the HIFU irradiation of the liver though the thorax. The main side effect of the operation reduces to overheating of the ribs and overlying tissue, including skin, caused by the strong absorption of ultrasound in the bones and its reflection from the bones.

bones is an order of magnitude higher than that in soft tissues. Acoustic impedances also strongly differ, resulting in the reflection of the ultrasonic energy from ribs. Another complication consists in a drastic decrease in the intensity of focused ultrasonic radiation caused by the same reason, which can become insufficient to damage tissues located behind the thorax. Recent experimental data give evidence that during direct irradiation of the liver through the thorax, ribs, and skin are heated even more strongly than tissue in the focal area. Of course, this is not admissible.

This problem was solved after the development of high-power two-dimensional phased therapeutic lattices and the elaboration of new HIFU irradiation protocols. Researchers of the Chair of Acoustics, Physics Department at Moscow State University, in collaboration with researchers at the Andreev Acoustic Institute, as well as the Imperial College and the National Physical Laboratory (NPL) in Great Britain, have developed and trialed a new method minimizing the action of ultrasound on ribs and preserving the high radiation intensity at the focus during irradiation of the liver [12, 13]. The method in the simplest version is based on the detachment of the lattice elements facing the ribs, so that ultrasound is transmitted to the focal spot mainly through intercostal gaps. The more complex modification of this method uses specially synthesized amplitude and phase field distributions over lattice elements, permitting to weaken diffraction effects during the propagation of ultrasound through the thorax, thus providing an electron scan of the focal point and constructing the configuration from several foci.

The operating capacity of the method has been confirmed in a joint experiment performed at the NPL. A lattice 170 mm in diameter with the radius of curvature of 130 mm, consisting of 254 elements 7 mm in diameter at a frequency of 1 MHz was used [12]. The possibility of a local damage to tissues located behind thoracic bones was demonstrated *in vitro*. In this case, the classical diffraction effect predicted theoretically was observed: two secondary maxima appeared in the focal plane behind the ribs along with the main focus. The mechanism of this effect is based on the interference of ultrasonic waves from two or more spatially separated sources which are intercostal gaps [14]. In this case, three corresponding areas of damage are produced in the tissue, which should be taken into account in the development of clinical protocols. These studies have given new data on the mechanisms of effects appearing during the propagation of HIFU through acoustic obstacles and provided the quantitative estimates of the focus splitting effect, which is important for practical implementations. The data obtained demonstrate the principal possibility of the application of this method in clinics for the destruction of tissues located behind thoracic bones without the overheating of bones and overlying tissue.

Experimental demonstration of the efficiency of coherent methods for seismoacoustic sounding of the sea bottom. The standard, modern, seismic, sea prospecting approach to determining the profile of an inhomogeneous bottom structure containing numerous reflecting layers is based on the use of incoherent pulsed sources (as a rule, pneumatic guns or sparkers) and extended receiving antenna systems (seismic braids). High-power pneumatic guns provide the signal level in the low-frequency range (down to 100 Hz), which, taking into account the directivity of the extended receiving antenna, is sufficient for achieving the required sounding depths (up to several kilometers). The spatial resolution of the method with such radiators can be improved by decreasing the signal duration, which is bounded from below by the design of the setup and is no less than ≈ 10 ms, which for the characteristic speed of sound in bottom deposits provides a resolution of about several dozen meters.

The application of coherent methods in seismic investigations offers a number of advantages related, first of all, to the possibility of using a prolonged coherent accumulation of received signals [15–17]. In this case, so-called complex signals, broadband modulated signals with a large base (the product of the pulse duration T by its spectral width F), are most interesting for practical implementations. Such signals are known to possess an autocorrelation function with the characteristic width of the main maximum smaller than the signal duration by a factor of FT ($FT \gg 1$). This means that, after the convolution of the received signal with the reference radiation, almost all the power of this signal is concentrated in the narrow maximum of the correlation function, which is in fact equivalent to a short pulse, but with a considerably higher emitted power (FT times higher). In addition, if the repeatability of signals is good enough, the energy of a long train of signals can be coherently accumulated, which also increases the sounding depth. As a result, the emitted signal power can be considerably reduced to provide the required sounding efficiency — the depth and (or) contrast of the structure of the bottom layers under study. Moreover, this energy gain allows one to consider the possibility of using high-frequency signals (up to ≈ 1 kHz) for seismoacoustic sounding. The application of high-frequency signals establishes conditions for a higher spatial resolution and considerably simplifies the technical realization of the system as a whole.

It should be emphasized that the peculiarities of the coherent approach are in no way specific for marine seismography. On the contrary, they are widely used in radiophysical methods for sounding inhomogeneous media. However, sources emitting signals with coherent properties sufficient for practical demonstration of the above-mentioned advantages are not employed in marine seismic prospecting at present.

In the last two decades, researchers at the Institute of Applied Physics (IAP), RAS have developed a number of high-power hydroacoustic sources emitting highly stable and well-controllable signals in the frequency range from a few hundred hertz to a few kilohertz, including broadband complex signals. This has opened up the real possibility for developing a coherent approach to seismic prospecting of the sea bottom. The commonly used in this situation signals are either linearly frequency-modulated (LFM) or phase-modulated (so-called pseudorandom). These signals provide approximately the same spatial resolution, and by using computer-controlled radiators, one or another regime of the signal formation can be realized. The stability of the sources themselves is limited only by the technical parameters of the master oscillators. Due to the digital control of radiation, any of the possible coherent approaches can be realized, namely: the matched filtration and convolution with the reference signal, the long accumulation of a train of signals, and the synthesis of an extended aperture by a single receiver (signal accumulation through a space coordinate) and the corresponding formation of its directivity.

Researchers at the IAP, RAS and the Institute of Oceanology, RAS have performed a number of joint

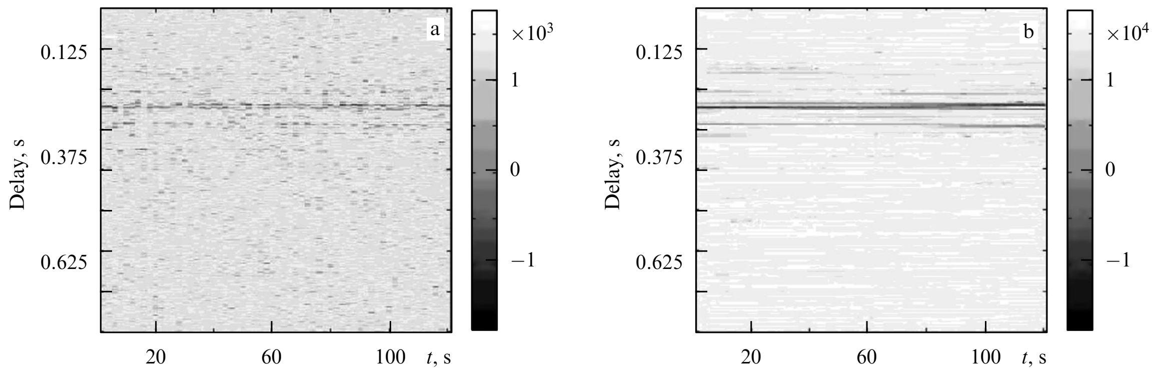

Figure 5. Portions of a seismogram corresponding to an individual bottom layer, obtained without the coherent accumulation of a train of pulses (a) and with the accumulation of a train of 16 coherent pulses (b). The time delay interval of 0–1000 ms corresponds to a depth of up to $\approx$ 1000 m.

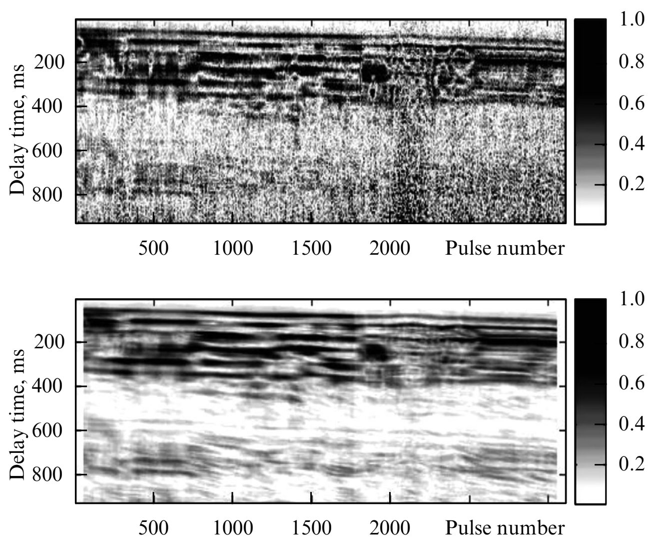

Figure 6. Seismograms obtained after sounding sea depth by LFM signals in the frequency band 180–230 Hz without interpulse accumulation (a) and by using the adaptive path accumulation of a train of up to 100 pulses (b).

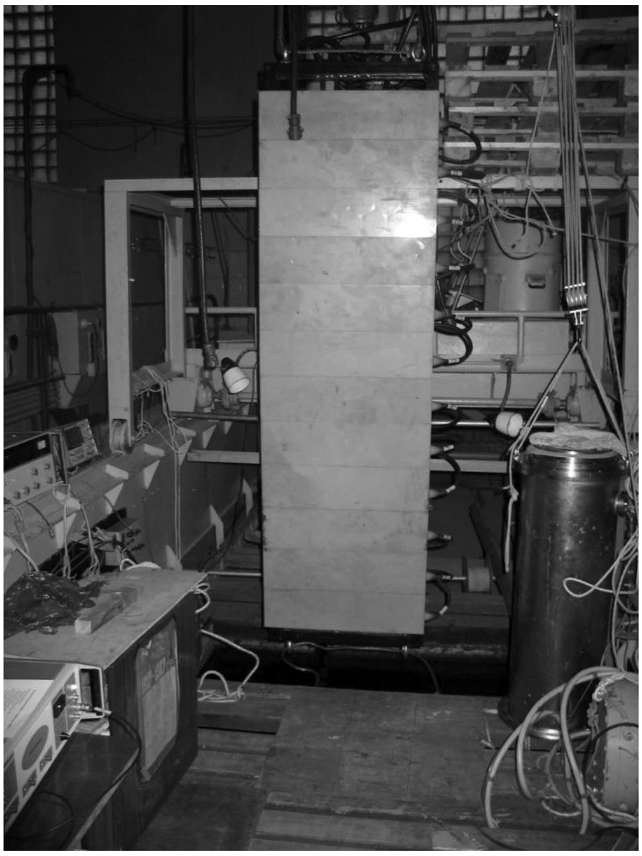

Figure 7. Parametric antenna before tests in a hydroacoustic pool.

experiments in the Caspian Sea, demonstrating the possibilities of coherent methods in marine seismoacoustics [18]. Hydroacoustic radiators were used, which generated synchronized trains of LFM pulses in different frequency bands ($\approx 50-100$ Hz) within a broad range ($\approx 100-1000$ Hz); the maximum radiation intensity of about 130 W was emitted in the frequency band from 180 to 230 Hz. The ultrasonic radiation was detected with a seismic braid consisting of 25 in-phase hydrophones. The coherent processing of received signals (reflected from bottom layers) included the matched filtration of individual pulses (convolution with the reference signal) and accumulation of a train of signals. The accumulation duration was limited by variations in the submersion depth of the radiator and variations in the bottom structure. The possibility of the coherent accumulation of a train of pulses reflected from bottom layers under particular experimental conditions was limited to the interval of $\approx 100-200$ s for the towing of a hydroacoustic radiator at the rate of three knots. This allowed efficient accumulation of up to a few dozen pulses (≈ 30). To improve the reconstruction quality of the bottom structure, a method was developed for accumulating pulses in paths in layers, taking into account the slopes of individual reflecting layers, which provided not only an increase in the number of pulses in the coherent train (up to a few hundred in practice) but also allowed adaptively estimating these slopes. Notice that most of the received signals had low noise stability (the signal-to-noise ratio was no more than 5 dB). However, the advantage in the signal-to-noise ratio after coherent signal processing reached 30 dB, which permitted the determination of the structure of bottom layers at depths of up to approximately 1000 m.

Figures 5 and 6 demonstrate the results of sounding a bottom structure along one of the paths. Fragments of the structure containing weakly contrasting layers were revealed

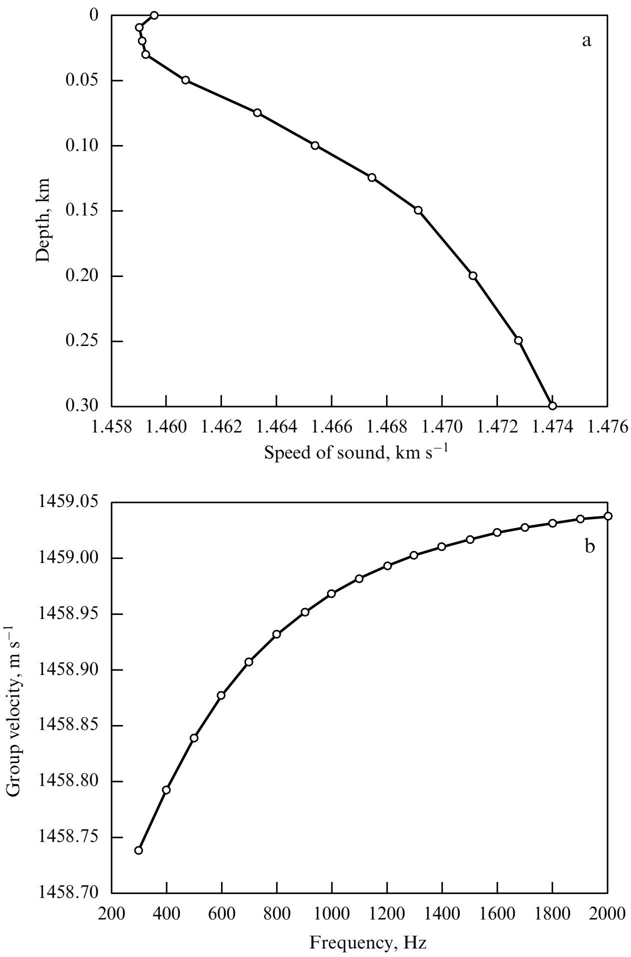

Figure 8. (a) Profile of the speed of sound in the Black Sea in February–March. (b) Frequency dependence of the group velocity of the first mode corresponding to the profile in Fig. 8a.

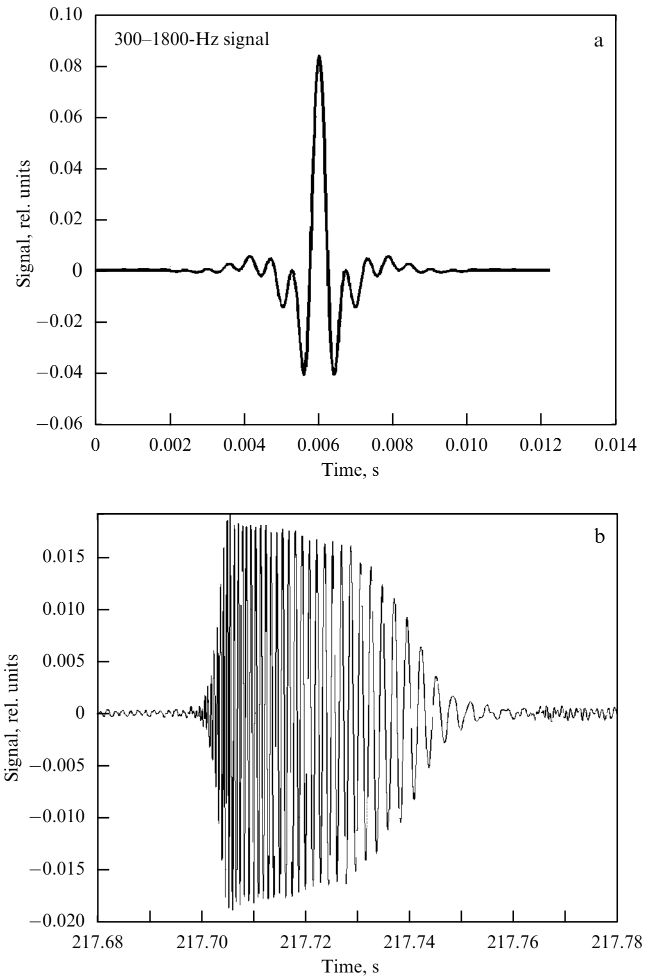

Figure 9. Influence of the frequency dispersion on the propagation of an acoustic signal in a Black Sea waveguide (Fig. 8a). (a) Pulse in the frequency band from 300 to 1800 Hz. (b) Same pulse at a distance of 318 km: first, high frequencies propagate, and then the low frequencies; the pulse duration at this distance is about 50 ms.

after the accumulation of trains consisting of up to 100 pulses. At the same time, only the autocorrelation compression of individual pulses did not provide a noticeable contrast in the case of a relatively small (≈ 10) base of LFM signals used in the experiments. The latters have shown that the seismoacoustic sounding of the sea bottom structure at depths of up to ≈ 1000 m with high spatial resolution can be performed by using comparatively low-power (≈ 100 W) high-frequency (up to a few hundred hertz) coherent hydroacoustic sources.

Development of a pilot parametric acoustic antenna for ocean studies. Researchers at the Andreev Acoustic Institute and the Taganrog Technological Institute, South Federal University have developed a parametric antenna for monitoring sea areas at long paths and constructed a pilot. This work was performed within the framework of a project of the International Scientific and Technological Center and was supported by the European Union. A specific feature of this hydroacoustic antenna, operating on the principles of nonlinear acoustics, is the extremely narrow directivity diagram for low-frequency acoustic signals. The width of the diagram for the parametric antenna is almost constant in a broad frequency range. A sounding signal is formed in the sea medium, which is excited by the high-power, high-frequency intensity-modulated acoustic pump. The high-frequency pump is detected due to nonlinear interaction and a traveling-wave antenna is formed in the sea medium, which generates a sharply directed acoustic signal at the modulation frequency. Such a low-frequency acoustic signal emitted parametrically will further propagate in the sea depth independently of the high-frequency pump. Due to the nonresonance method of low-frequency signal generation, the parametric antenna emits sounding signals in an extremely broad frequency band (more than two octaves). Therefore, the realization of this project will allow the testing of a principally new emitting nonlinear-acoustic system for long-path sounding of sea areas and the ocean. This acoustic system (Fig. 7) has a comparatively small size (the emitting aperture size is 0.7×2 m^2), a broad signal frequency band (300–3000 Hz), and a high radiation directivity (no worse than $2°$ in the vertical plane) in the entire frequency range. These characteristics allow a good matching between directed parametric radiation and a waveguide structure in the sea.

At present, this antenna is being tested in the water area of the Sukhumi Hydrophysical Institute in Abkhaziya. The calculated characteristics of the parametric antenna should provide single-mode excitation of a sea waveguide efficient for monitoring the Black Sea or ocean investigations at distances of up to 1000 km. Notice that the possibility of applying a parametric antenna for long-path ocean studies was first demonstrated almost 20 years ago [19, 20].

The obtained characteristics of this parametric antenna allow studying the frequency dispersion during the propagation of an acoustic signal in a sea waveguide. Figure 8a displays the depth distribution of the sound speed typical for the Black Sea in the spring. This distribution causes changes in the propagation velocity of signals at different frequencies. The frequency dependence of the group velocity for the first mode of this waveguide is plotted in Fig. 8b. One can see from this figure that the dispersion during the propagation of a broadband signal in the frequency range lower than 2 kHz can be noticeable. Figure 9 shows the influence of this dispersion on the propagation of an acoustic signal in a Black Sea waveguide in the frequency band from 300 to 1800 Hz. One can see that, due to dispersion, the signal duration under these conditions changes by a factor of almost 25 along with the corresponding change in the signal intensity. This effect will be more pronounced at longer paths. Preliminary experimental studies of the propagation of acoustic radiation from a parametric antenna in a shallow-water waveguide [21] have revealed that, if the frequency modulation is matched with the waveguide, the duration of the emitted signal decreases, resulting in an increase in the signal-to-noise ratio and, hence, in the efficiency of acoustic means in a sea waveguide.

Thus, this new tool for ocean investigations establishes conditions for the selective excitation of modes in a broad frequency range, which in turn opens up the possibility of studying a new ocean characteristic — the frequency dispersion of signals in a waveguide. The study of this characteristic will complement our knowledge about the propagation of acoustic signals in ocean waveguide structures.

References

1. Preobrazhensky V et al. *J. Magn. Magn. Mater.* **322** 585 (2010)
2. Yevstafyev O et al. *J. Magn. Magn. Mater.* **323** 1568 (2011)
3. Ozhogin V I, Preobrazhenskii V L *Usp. Fiz. Nauk* **155** 593 (1988) [*Sov. Phys. Usp.* **31** 713 (1988)]
4. Brysev A P, Krutyanskii L M, Preobrazhenskii V L *Usp. Fiz. Nauk* **168** 877 (1998) [*Phys. Usp.* **41** 793 (1998)]
5. Preobrazhenskii V L *Usp. Fiz. Nauk* **176** 108 (2006) [*Phys. Usp.* **49** 98 (2006)]
6. Preobrazhensky V, Bou Matar O, Pernod P *Phys. Rev. E* **78** 046603 (2008)
7. Khokhlova V A *Programma Mezhdunarodnogo Onkologicheskogo Nauchno-obrazovatel'nogo Foruma ONKOKHIRURGIYA-2010 "V Budushchee cherez Novye Tekhnologii"* (Program of the International Oncological Scientific and Educational Forum 'Oncology Surgery-2010: To the Future through New Technologies', Moscow, May 31–June 2, 2010) p. 7; http://www.oncology.ru/events/2010/05/31/program/program.pdf
8. Canney M S et al. *Ultrasound Med. Biol.* **36** 250 (2010)
9. Canney M S et al. *J. Acoust. Soc. Am.* **127** 1760 (2010)
10. Kreider W et al., in *2nd Intern. MRgFUS Symp.: Current and Future Applications of MR-guided Focused Ultrasound, October 17–20, 2010, Washington, DC, USA*, p. 79
11. Bessonova O V et al. *Akust. Zh.* **56** 380 (2010) [*Acoust. Phys.* **56** 354 (2010)]
12. Bobkova S et al. *Ultrasound Med. Biol.* **36** 888 (2010)
13. Gavrilov L R et al. *Meditsin. Fiz.* (3(47)) 53 (2010)
14. Khokhlova V A, Bobkova S M, Gavrilov L R *Akust. Zh.* **56** 622 (2010) [*Acoust. Phys.* **56** 665 (2010)]
15. Lebedev A V, Malekhanov A I *Izv. Vyssh. Uchebn. Zaved. Radiofiz.* **46** 579 (2003) [*Radiophys. Quantum Electron.* **46** 523 (2003)]
16. Averbakh V S et al. *Akust. Zh.* **45** 5 (1999) [*Acoust. Phys.* **45** 1 (1999)]
17. Averbakh V S et al., in *Fundamental'nye Issledovaniya Okeanov i Morei* (Fundamental Studies of Oceans and Seas) Vol. 2 (Ed.-in-Chief N P Laverov) (Moscow: Nauka, 2006) p. 500
18. Lazarev V A et al. *Akust. Zh.* (in press)
19. Esipov I B et al. *Akust. Zh.* **39** 173 (1993) [*Acoust. Phys.* **39** 89 (1993)]
20. Esipov I B et al. *Akust. Zh.* **40** 71 (1994) [*Acoust. Phys.* **40** 61 (1994)]
21. Esipov I B et al. *Akust. Zh.* **55** 56 (2009) [*Acoust. Phys.* **55** 76 (2009)]