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ON 80th ANNIVERSARY OF VICTORY IN GREAT PATRIOTIC WAR

Acoustics and the Defense of the Fatherland *

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Contents

Abstract. This paper provides a brief overview of the main achievements in applied acoustics that served defense needs during the Great Patriotic War and their subsequent development. The review is arbitrarily divided into three sections: (1) underwater sound, (2) aerial acoustics, and (3) medical applications. Each section provides historical information on the most important developments during the war years, as well as related progress after Victory. The physical phenomena underlying these technical solutions are outlined, and the acoustic specificity is emphasized.

Keywords: sonar, underwater sound, noise direction finders, marine and aviation acoustics, parametric transmitting arrays, submarines, mine and torpedo weapons, direction finding, aircraft, medical ultrasound

1. Introduction

A brief overview of the three main sections.

Underwater sound. The early ideas and work of Konstantin Vasil'evich Shilovskii and Paul Langevin. The use of the piezoelectric effect in sonar. World War I, losses in underwater battles. Demagnetization of ships (Anatolii Petrovich Aleksandrov, Igor' Vasil'evich Kurchatov) and the transition from magnetic to acoustic mine detonators (Rudolf Hell). Ultra-long-range sound propagation in the ocean, the discovery of an underwater sound channel (Maurice Ewing, Leonid Maksimovich Brekhovskikh, Lazar' Davidovich Rozenberg). The advent of the nuclear fleet and anti-submarine underwater missiles. Vector sound receivers. Signal transmission over air-to-water channels. Nonlinear phenomena and parametric antennas.

Aerial acoustics. Passive acoustic means of aircraft detection (in the pre-radar era, 1917–1940). Gun guidance stations. Intense sound in the air. The effect of high-power emitters and sonic boom waves. Vladimir Mikhailovich Myasishchev's 'Hellish Mower.' Research into the development of next-generation supersonic passenger aircraft and the targeted transmission of sound signals with a beam of high-intensity ultrasound (US).

Medical applications. The development of ultrasound diagnostics from 1942 to the advent of modern sonographs (ultrasound instruments). High-intensity US in the post-war years. The first steps in acoustic surgery (brothers Frank and Bill Fry, Andrei Konstantinovich Burov). Modern use of nonlinear US. Radiation pressure, elastography. Thermal, force, and shock-wave effects.

2. Specifics of acoustics

The presentation at the session of the RAS Physical Sciences Division was tailored to the interests of the physics audience. Therefore, it seemed logical to remind physicists of the specifics of acoustics understood in a broad sense. Its primary characteristic is the diversity of its topics and their dispersal across all of the RAS's natural science divisions. Physics traditionally accounts for only about 20% of all acoustics problems.

Acoustics is the concern of the Division of Geosciences (waves in the atmosphere, ocean, and geophysical structures), the Division of Energy, Mechanical Engineering, Mechanics, and Control Processes (technical acoustics, noise and vibra-

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tion, marine and aviation acoustics, industrial diagnostics), the Division of Mathematical Sciences (modeling, numerical techniques, mathematical physics, inverse problems), the Division of Biological Sciences and the Division of Physiological Sciences (waves in living systems and tissues, effects on organisms), the Division of Medical Sciences (acoustic diagnostics, therapy, and surgery), the Division of Nanotechnology and Information Technology (message processing and transmission, computer science), and the Division of Chemistry and Materials Sciences (effects on reactions, technologies, structure formation, metamaterials). There are also sections that study speech formation and perception, the acoustics of echolocating animals, architectural acoustics, the acoustics of musical instruments, electroacoustics, and a wealth of other important problems usually found outside the physical sciences.

This applies to the formal titles of the specialties of prominent scientists who worked in the field of acoustics. Here is information about some academicians [1].

Viktor Anatol'evich Akulichev (mechanics, oceanology), Nikolai Pavlovich Aleshin (metallurgy and structural materials, including metal welding technology, materials diagnostics), Nikolai Nikolaevich Andreev (acoustics), Leonid Maksimovich Brekhovskikh (oceanology), Fedor Vasil'evich Bunkin (physics), Andrei Viktorovich Gaponov-Grekhov (physics), Georgii Sergeevich Golitsyn (atmospheric physics), Yurii Vasil'evich Gulyaev (element base, computer materials and diagnostics), Grigorii Ivanovich Dolgikh (oceanology), Yurii Nikolaevich Kul'chin (nanotechnology), Evgenii Anatol'evich Mareev (atmospheric physics), Vladimir Elifer'evich Nakoryakov (thermal physics), Robert Iskanderovich Nigmatulin (mechanics), Sergei Apollonovich Nikitov (computing, location, telecommunication systems and element base), Vladimir Grigor'evich Peshekhonov (control processes), Vladislav Ivanovich Pustovoit (automation, including scientific instrumentation), Aleksandr Aleksandrovich Kharkevich (mechanics and control processes).

We point out other frequently overlooked features of acoustics.

Acoustic problems are distinguished by their enormous range: from 10^{-13} cm (the droplet model of atomic nuclei) to intergalactic scales (the formation of galactic structures).

Figure 1 illustrates the dynamics of an atomic nucleus within the framework of the simplest droplet model. The modes of small acoustic oscillations of a spherical droplet (upper diagrams in Fig. 1) were calculated by John William Strutt (Lord Rayleigh) [2]. As the amplitude increases, the oscillations become nonlinear (lower diagrams). The sphere takes on a 'dumbbell' shape and breaks into two parts. Strongly nonlinear acoustic oscillations of a droplet nucleus can be excited by the impact of a neutron on a heavy nucleus. This results in nuclear fission, neutron multiplication, and a chain reaction: a nuclear explosion.

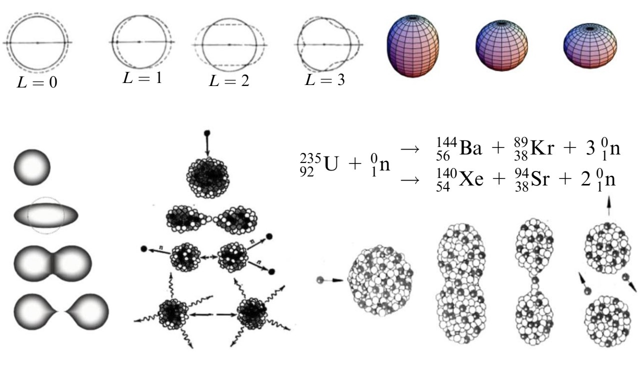


Figure 1. Acoustic vibrations within framework of liquid droplet model of nucleus.

Figure 2 illustrates the opposite case of extremely large scales. As is well known, acoustic waves were responsible for the structure formation of the Universe after the Big Bang [3]. Figure 2a shows a map of the anisotropy of the cosmic microwave background radiation corresponding to the distribution of baryonic matter. This distribution was produced by acoustic density waves generated in the early Universe when it was filled with hot plasma.

Figure 2b depicts clots of interstellar matter formed by particle flows. Cellular structures of galaxies are produced. The process is described by the 3D Burgers equation, the fundamental equation of nonlinear acoustics. This is a modified Zel'dovich model (Sergei Nikolaevich Gurbatov–Aleksandr Ivanovich Saichev–Sergei Fedorovich Shandarin) [4]. In terms of wave physics, clots of matter correspond to shock fronts.

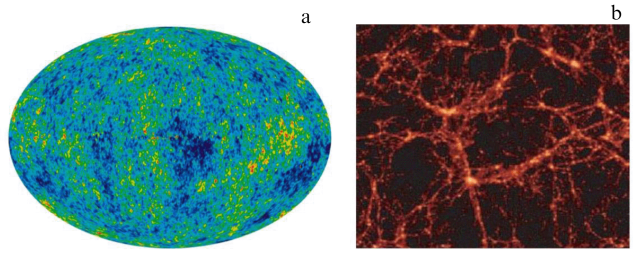


Figure 2. (a) Distribution of matter density in Universe produced by elastic waves; (b) formation of fronts (shock waves) in approximation of Yakov Borisovich Zel'dovich.

Another feature is the unique penetrating ability of acoustic waves. Sound propagates underwater for thousands of kilometers, penetrates Earth and the human body. Figure 3a shows the long-range sound propagation path in the Indian Ocean: from the shores of Australia to the Chagos Archipelago. The measurements were performed by staff members of the Department of Acoustics at M.V. Lomonosov Moscow State University (MSU). Figure 3b shows the result of acoustic probing to a depth of 15 km at the Shugo mud volcano [5]. The structure of Earth's core (the presence of a solid inner and liquid outer core) was also established using acoustic techniques (Fig. 3c). This structure was later refined relying on new seismic data [6].

The lower panels of Fig. 3 are an acoustic visualization of the face of a baby in the womb (Fig. 3d) as well as the result of diagnostics of a crack inside a vibrating plate (the picture of 'parasitic' bends of the surface at the fundamental frequency (Fig. 3e) and the crack itself when recording the seventh harmonic (Fig. 3f)).

To summarize, it should be noted that acoustics is focused primarily on applications. The share of fundamental research in it is small. It deals little with the study of the properties of matter, space-time, and the Universe. However, acoustics has markedly influenced work that is generally considered fundamental. One can point out effects that had been known to acousticians long before their authors received recognition in other areas of physics. This is, of course, the radiation during supersonic motion of a body, which was

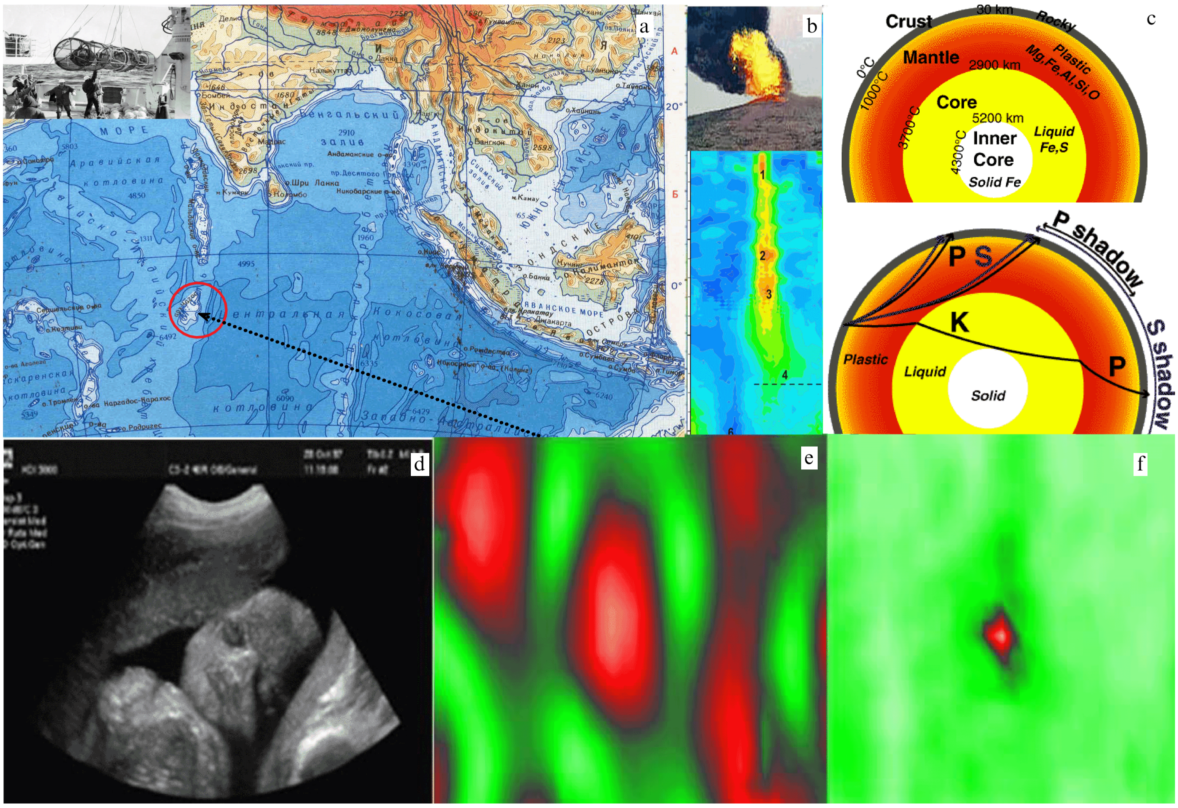


Figure 3. Examples of unique penetrating power of acoustic waves. (a) Long-range sound propagation path in Indian Ocean. (b) Deep section of mud volcano. (c) Cross section of Earth: highlighted are solid inner and liquid outer core, mantle, and crust. In seismic science, use is made of following notation: *P* is longitudinal wave in mantle or crust, *S* is shear wave in mantle or crust, *K* is wave in outer core. Bottom row: (d) face of baby in womb, (e) surface relief of plate oscillations, (f) nonlinear response of internal crack.

described by Doppler in 1847 (see Ref. [7]) and gained attention for its weak optical analogue: the Sergei Ivanovich Vavilov–Pavel Alekseevich Cherenkov effect [8] (the 1958 Nobel Prize in Physics: Igor' Evgen'evich Tamm, Il'ya Mikhailovich Frank, Pavel Alekseevich Cherenkov). The acoustic effect is much stronger than the optical one; the shock 'Mach wave' from a supersonic aircraft flying at low altitude can be used as a weapon (see Section 4).

In 1987, Arthur Ashkin made 'laser tweezers' to hold and move molecules, and transplanted bacteria and viruses from one sample to another [9] (2018 Nobel Prize in Physics). The basis is the pressure of light, observed by Petr Nikolaevich Lebedev in 1899. However, few people paid attention to the obvious fact: the pressure of sound is 100,000 times stronger. Therefore, it was observed by Michael Faraday back in 1831 (see Ref. [10]), and 'ultrasonic tweezers' already existed long before A. Ashkin (Robert Apfel, see Ref. [11]). The second force acting in laser (acoustic) tweezers is proportional to the gradient of the energy density averaged over fast oscillations. In microwave physics, it is known as the Andrei Viktorovich Gaponov–Mikhail Adol'fovich Miller force [12].

Transition radiation of electromagnetic waves, predicted by Vitalii Lazarevich Ginzburg and Il'ya Mikhailovich Frank in 1945 [8], is discussed less frequently in acoustics than in optics. However, the acoustic effect in this case, too, is much stronger than the optical one. It has been observed (heard) by every passenger on a train moving across a bridge with periodically spaced trusses, or when driving in a car past a series of columns or other structures that make up strong boundary nonuniformities.

These are interesting examples. A complete list of 'priority' acoustic phenomena is not the purpose of this paper.

3. Underwater sound

In 1912, Russian engineer Konstantin Vasil'evich Shilovskii (Fig. 4) came up with the idea of a device based on the emission of an ultrasonic (US) beam and its reflection by an obstacle [13]. Shilovskii devised an echo sounder to prevent ships from colliding with floating ice floes. Let us remember that the *Titanic* collided with an iceberg in 1912. During World War I, it became necessary to employ a sonar to detect German submarines, which had sunk several British cruisers and the liner *Lusitania* (1200 lives lost). Shilovskii, who was then living abroad, sent the following letter to the French government: "If you take a completely flat plate measuring 1 m by 1.5 m, completely immersed in water, and make it vibrate at a frequency of up to 100 kHz, it will emit a stream of mechanical energy into the water, which we may call 'ultrasonic.' Everything that is known about the propagation of sound in water leads us to the conclusion that the absorption coefficient of sound energy in water is very small, much smaller than for light, and as a result, this energy will propagate underwater at the speed of sound over very long distances.... Therefore, it is possible... to emit... rays of 'mechanical light,' ... illuminating the darkness under water, dispersing it and searching there for what needs to be found: mines, submarines, etc."

Konstantin Vasil'evich Shilovskii implemented his idea in 1916 together with P. Langevin (see Fig. 4). It involved exciting a cylindrical mica capacitor with a high-

Figure 4. Konstantin Vasil'evich Shilovskii and Paul Langevin.

frequency sound generator, producing inaudible US vibrations.

In 1917, Paul Langevin turned his attention to the potential of the piezoelectric effect, discovered by Jacques and Pierre Curie in 1880, to make transmitters and receivers for underwater use. He used a quartz receiver and a vacuum tube amplifier, and in 1918 he produced a transducer based on steel–quartz–steel layers. With its help, the signal transmission range was lengthened to 8 km.

During World War I, a start was made on the detection of submarines with passive hydrophones. Later, active sonars were developed. The following figures serve to illustrate the combat effectiveness of submarines. Surface ships sank 217 ships in World War I, while submarines sank approximately 6000. This fact motivated both the mass construction of submarines and the development of more sophisticated sonar equipment.

Developed during World War II were acoustic-guided torpedoes, acoustic naval mines, and scanning sonar. In total, Germany lost 781 submarines.

By the onset of the war, 176 of the 213 submarines in the USSR were equipped with Mars-type hydrophones. Some were also equipped with Vega and Sirius underwater communication stations and British Dragon sonars. Surface ships were also being equipped with underwater sound communication stations, echo sounders, and sonars [14]. Improvements in equipment and tactical techniques for its use made it possible to shift to covert attacks without periscopes. The first was carried out in 1943 by the M-171 submarine (commander G.D. Kovalenko, sonarman A.M. Lebedev). In 1945, the crew of the S-13 (commander Aleksandr Ivanovich Marinesko, sonarman I.M. Shpantsev) destroyed the liner *Wilhelm Gustloff* and the transport *General von Steuben* with a total displacement of 40,000 tons [14]. The heroic experience of the submariners was employed in the development of more advanced technologies in the post-war years.

At the beginning of the war, Germany actively used bottom magnetic mines. The proximity explosive device was triggered by the presence of an enemy ship within the mine's detection range. It responded to the distortion of Earth's magnetic field at a distance of up to 35 meters from the mine. The British strived to clear the entrances to their ports of mines by active use of minesweeping. They unraveled the mines' design and learned how to 'trick' the magnetic detonator. The USSR adopted the method of demagnetizing ship hulls. Corresponding methods were developed by Anatolii Petrovich Aleksandrov and Igor' Vasil'evich Kurchatov.

The magnetic explosive device gradually lost its effectiveness. Therefore, German engineers invented a new acoustic fuse (Rudolf Hell, 1901–2002), which responded to the noise of a ship's propellers. The device was triggered if the noise had a frequency of approximately 200 Hz and doubled in intensity over 3.5 seconds. This is precisely the noise produced by a large-displacement warship. The mine did not respond to small vessels. The fuse in acoustic mines used a hydrophone to convert the noise into electrical pulses, which caused an explosion when a ship passed over it. Apart from mines that 'hear' a ship, the Germans also used combined magnetic-acoustic mines to increase the reliability of the fuse [15].

The Allies managed to unravel the details of German designs and make equally advanced acoustic weapons.

During the entire period of World War II, the navies of the warring states laid 675 thousand mines, which blew up and sank approximately 4000 ships and seriously damaged 8000.

Torpedoes with acoustic guidance systems inflicted significant losses on Allied transports and convoys. Unlike mines, they could use onboard sonars in both passive and active modes. Initially, the new weapon was highly effective. However, with the help of our sailors who had captured samples of German torpedoes, the British were able to develop simple noise simulators. These devices significantly reduced the effectiveness of acoustic torpedoes in combat.

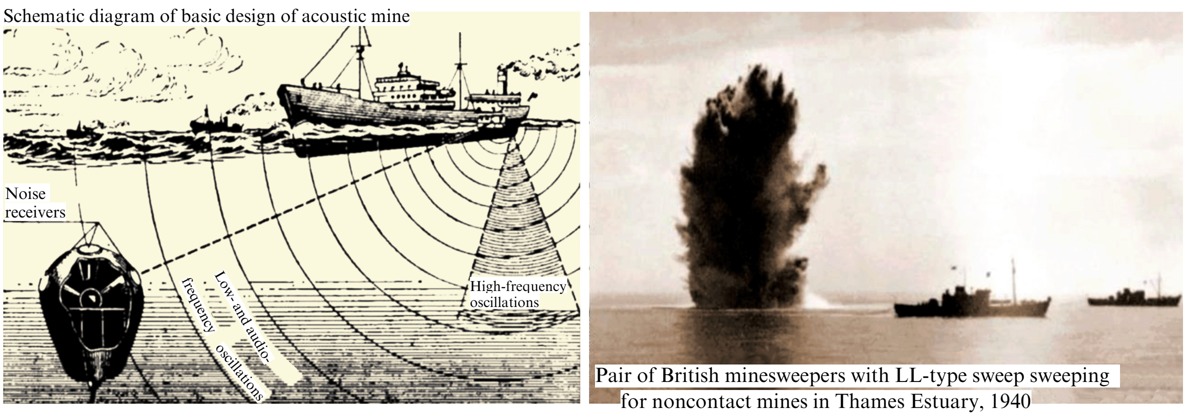


Figure 5. Acoustic mine triggering scheme (a) and magnetic mine trawling in Thames Estuary (b).

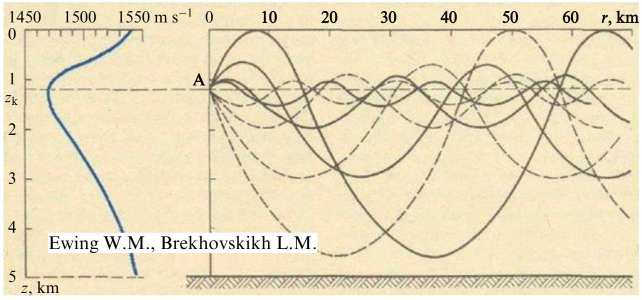


Figure 6. Depth profile of sound speed (with minimum on axis) in underwater sound channel and path of rays from source located on axis of waveguide (see, for example, review by Brekhovskikh L., "Propagation of acoustic and infrasonic waves in natural waveguides over long distances," *Sov. Phys. Usp.* **3** 159 (1960); *Usp. Fiz. Nauk* **70** 351 (1960)).

In 1945, Maurice Ewing managed to detect the sound of a small explosion at a distance of over 3000 km. The sound propagated in an underwater sound channel (USC, Fig. 6). Soon after the war, Leonid Maksimovich Brekhovskikh and Lazar' Davidovich Rozenberg, when analyzing signals from underwater explosions, discovered a USC in the Pacific Ocean [16].

It is pertinent to note that, as regards scientific sophistication, German and British acoustic systems were outpacing USSR developments during the war. In the postwar years, domestic hydroacoustic weapons began to improve rapidly. Dozens of Stalin, Lenin, and USSR State Prizes were awarded for work in the area of military acoustic applications (approximately 200 laureates in all). The history of domestic hydroacoustics (through the example of the work of the Okeanpribor Concern) is described in detail in Ref. [17].

After the end of the Great Patriotic War, a start was made on a thorough study of the noise sources of surface and submarine ships, and soundproofing and active noise reduction systems were developed. Special attention was paid to the acoustic silence of nuclear submarines, the basis of the strategic weapons triad. It was precisely the strategic missile submarines that ensured, thanks to their stealth, the peaceful development of the Fatherland all these years.

For example, a special propeller design with sickle-shaped blades and serrations was proposed, resulting in a small scale and rapid attenuation of break-away vortices. Special measures were taken to prevent cavitation-induced erosion. Gas bubbles, which form cumulative high-speed (approximately a km/h) jets of water, not only destroy the propeller but also produce strong acoustic fields (Fig. 7).

The submarine's hull is lined with special rubber plates that absorb both external sonar sounds and internal noise. The hydroacoustic plates are attached to the submarine's lightweight hull on the outside using sealant, secured with special screws, and coated with protective paint. Each plate weighs approximately 80 kg, and up to several thousand of these plates are required for a single submarine.

Also noteworthy is the emergence of underwater missiles as a development of torpedo weapons. The history of their development and adoption into service is a significant event for the defense of the Fatherland. In the early 1950s, the United States developed a high-speed nuclear submarine fleet, which proved difficult to counter with conventional torpedoes. Parity was achieved precisely due to the high speed of our underwater missiles.

Figure 8 shows the RAT-52 rocket-propelled torpedo designed by Grigorii Yakovlevich Dillon. The problem arose with acoustic target guidance under the intense noise of jet engines. Researchers from the Physics Department of Moscow State University played an active role in solving the problem. The results are described in Ref. [18]. The primary authors are Aleksandr Vasil'evich Minaev, a graduate of the Chair of Acoustics and a senior official of the Defense Ministry, and Professor Yurii Mikhailovich Romanovskii, who, along with his colleagues, participated not only in the development of the equipment but also in test launches of these missiles. Valentin Andreevich Burov, a professor at Moscow State University, subsequently made a significant contribution to the development of guidance systems. Not only did he design but he also built a prototype of the onboard device (he was awarded the State Prize in 1980).

Naturally, it was not only our scientists who played a huge role in developing weapons to defend the Fatherland, but also, and above all, our engineers, technologists, and equipment designers. As mentioned above, acoustics is 'dispersed' across the departments of the Russian Academy of Sciences. Furthermore, there are a large number of design bureaus and factories manufacturing special-purpose equipment. This is absolutely necessary, since only a problem-oriented specialist, who is familiar with the history of specific devices and the details of technical solutions, is capable of implementing proper upgrades. However, in some cases, it is necessary to make equipment operating on 'new' (previously unused) physical phenomena. And here, scientists are indispensable. Scientists proceed from 'first principles' and can propose completely new solutions. I will provide a few examples.

Physicists are well acquainted with the A.V. Gaponov-Grekhov Institute of Applied Physics of the Russian Academy of Sciences (Nizhny Novgorod). During the last (2025) elections to the RAS, four 'young' scientists from this institute were elected as corresponding members of the Physical Sciences Division (for 11 vacant seats). Two people were elected as academicians. This is by far more than from

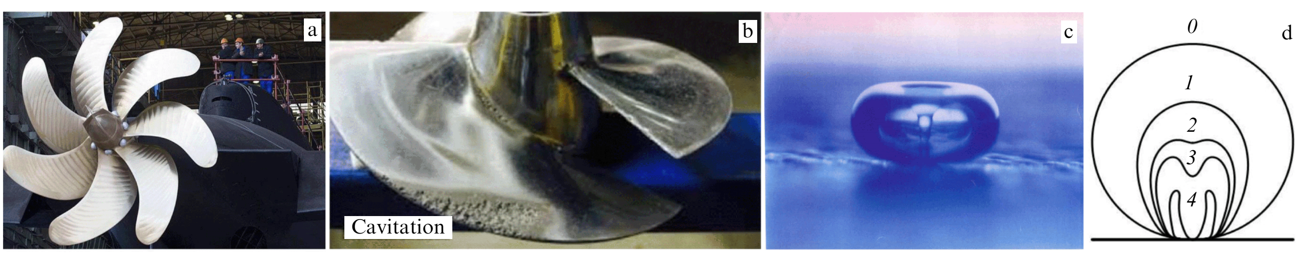


Figure 7. (a) Shape of propellers, (b) cavitation erosion of blades, (c) photograph (L. Crum) of collapsing bubble with production of high-speed cumulative jet, (d) collapse dynamics.

Figure 8. (a) Suspension of RAT-52 rocket torpedo (in service since 1953) on Il-28T (Photo: G.S. Shutov, http://www.bellabs.ru/Fotab/). *Aviation and Cosmonautics* journal no. 10 (2006). (b) In museum of concern Marine Underwater Weapons — Gidropribor. Leonid Evgen'evich Sobisevich, Oleg Vladimirovich Rudenko, and Sergey Nikolaevich Gurbatov standing in front of RAT-52 (photo: A.L. Sosibevich). (c) Book *Physical Problems and the History of the Development of Acoustic Guidance Systems,* published in 2011 (scientific editors: Aleksandr Vasil'evich Minaev, Yurii Mikhailovich Romanovskii, Oleg Vladimirovich Rudenko) [18].

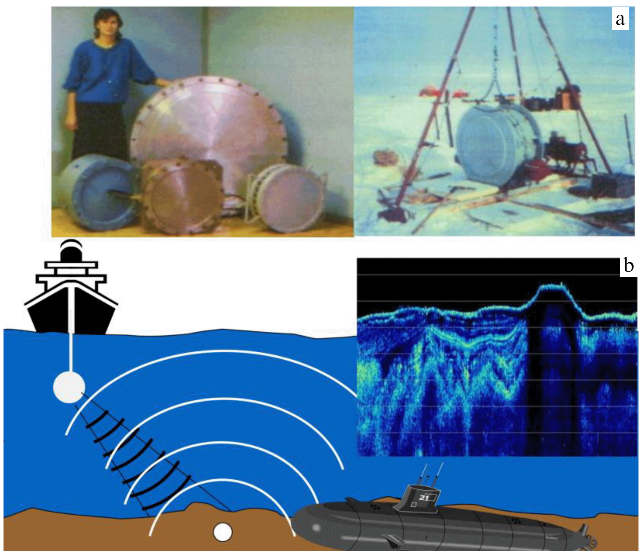


Figure 9. Examples of new problems that invited participation of physicists. Low-frequency emitter (a) and nonlinear 'parametric' sonar (profiling sedimentary layers (b)).

any other leading Russian institute. However, many think that this institute is renowned for its work on ultrahigh-power lasers and microwave devices (gyrotrons). Few remember that it was set up in 1977 to treat acoustic problems related to active sonar for the long-range detection of submarines. The institute advanced significantly, which technical centers failed to do. There, with the participation of staff members of the General Physics Institute of the Russian Academy of Sciences, efficient low-frequency (70–600 Hz) hydroacoustic emitters (Fig. 9) were developed for operation at a range of hundreds of kilometers.

Another example is nonlinear 'parametric' sound emitters (PEs) (see Fig. 9). A PE consists of a conventional source of high-intensity high-frequency 'pump' waves and an extended section of a nonlinear medium. This 'column' of water can be tens or hundreds of meters long. Excited in it is a weakly attenuating low-frequency wave and its directional pattern is formed. Using PEs at frequencies of several kHz, it is possible to produce very narrow 2°–5°-wide patterns with emitter dimensions of the order of tens of centimeters. For comparison: to do so, conventional sources must have an aperture diameter of approximately 10 m. Hydroacoustic PEs are employed to calibrate multicomponent antennas; for profiling the bottom and sediment layers, detecting objects under the bottom; for recording the frequency response of a target and classifying objects; for acoustic communication in shallow waters under conditions of bottom and surface reverberation; and in Doppler logs for absolute measurement of vessel speed. Much has been done by scientists from the Division of Acoustics at Moscow State University and the Taganrog Radio Engineering Institute [19].

A third example is new-generation high-speed underwater missiles. The principle proposed by scientists harnesses the phenomenon of 'supercavitation.' The missile flies underwater in a gas bubble at the speed of an airplane.

A fourth example is vector sound receivers. They have the unique ability to determine the direction of a source 'at a single point.' Obsolete acoustic pressure receivers consisted of a long tube with rubber bulbs attached to the ends (vibration receivers). The acoustician ('listener'), whose ears received signals from the bulbs through two waveguides, rotated the tube until the phase difference between the two signals turned to zero. The normal to the tube's axis then indicated the direction of the wave's arrival.

A diagram of a vector receiver is shown in Fig. 10. An acoustic wave acts on a sphere, whose oscillations can occur

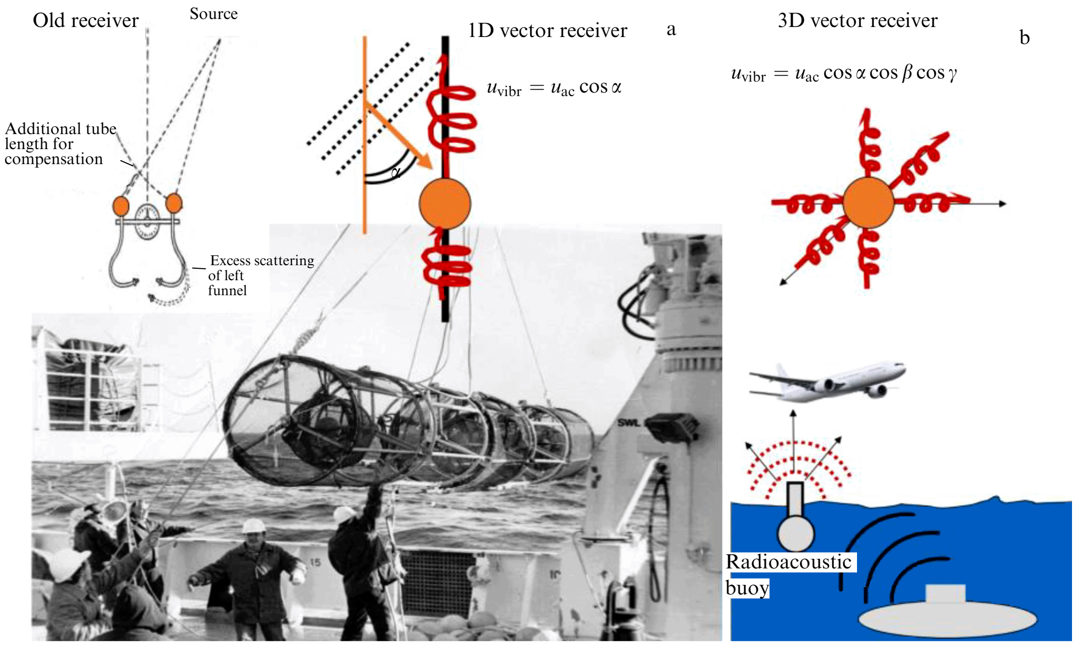


Figure 10. Vector receivers. Operating diagram, submersible multi-element antenna and hydro-radar.

only along the guide rods. In the one-dimensional case, the oscillation amplitude is proportional to the cosine of the angle between the wave vector and the direction of the rod. In the three-dimensional case, oscillations can occur along three coordinates. Three cosines indicate the direction of wave arrival. Real receivers, of course, have a different design: Sergei Nikolaevich Rzhevkin, in particular, treated the oscillations of a small sphere and showed that the oscillation velocity can be measured by placing a seismometer-type device inside it [20]. The ideas that originated in the group led by Sergei Nikolaevich Rzhevkin were picked up, developed, and brought to technical implementation in a number of prototypes accepted into service by employees of the Gidropribor Central Research Institute (now the Underwater Sea Weapons — Gidropribor concern). A significant contribution to their development was also made by staff members of VNIIFTRI (All-Russian Research Institute of Physicotechnical and Radiotechnical Measurements) and a number of other organizations.

Vector receivers are now produced in many countries. They are used, for example, in the most widespread models of sonobuoys. The buoy floats on the sea surface, receives a hydroacoustic signal from an underwater object, and transmits it via radio channel to an aircraft or satellite. Such buoys are either dropped en masse from aircraft or released from underwater onto the sea surface. They are inexpensive and well suited to the principles of modern warfare.

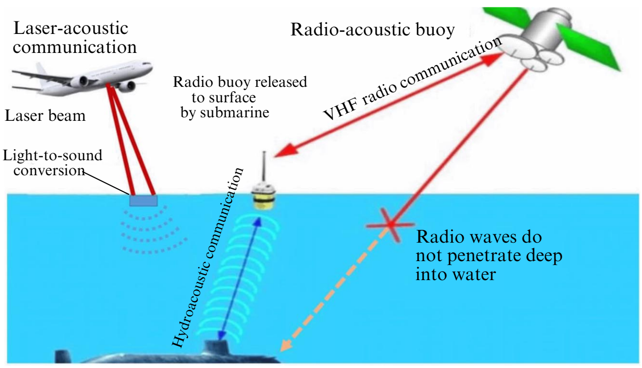


Figure 11. Possible communication channel systems between aerial and underwater objects (see, for example, review by L.M. Lyamshev, "Optoacoustic Sources of Sound," *Sov. Phys. Usp.* **24** (12) 977 (1981); *Usp. Fiz. Nauk* **135** 637 (1981)).

In addition to radioacoustic buoys, use is made of the optoacoustic effect (Fig. 11) to implement an air-to-water communication channel. A laser beam causes slight but rapid heating of a thin surface layer of water. The layer expands to generate an acoustic wave in the water.

4. Aerial acoustics

Even during World War I, reconnaissance of enemy artillery positions was performed using acoustic measurements. This allowed determining the location of guns, and return fire was directed at their coordinates.

During World War II, special sound batteries were used for 'sound-measuring' reconnaissance. They typically contained several microphones to record the arrival of a gunshot. Measuring the delay time allowed calculating the gun's coordinates. A return shot was then fired; the sound of the explosion was used to adjust aiming accuracy in the same way [21].

Acoustic sonars came into use with the advent of the first aircraft; they enjoyed wide use during the First and Second World Wars. Their design relied on directional receiving antennas, from which an amplified signal was transmitted to an acoustic operator via waveguides (Figs 12, 13).

During daytime and in the absence of interference, the loud sound of an engine made it possible to detect an aircraft several kilometers away. Optical devices (binoculars) were inferior to acoustics and only helped identify the aircraft (friend or foe). In poor weather conditions, the performance of the sound detector, of course, degraded. However, at night, as well as in heavy cloud cover and fog, aircraft became invisible; they could be detected only by acoustic emission.

Wind-related interference, in turn, significantly affected the sensitivity of acoustic systems. Detection range shortened during gusts of wind. Wind speeds exceeding 10 m s^{-1} made

Figure 12. Soviet sound detector ZT-5 (1941). During the war, it was improved by Yurii Mikhailovich Sukharevskii and Dmitrii Ivanovich Blokhintsev.

detection problematic. Furthermore, the wind produced noise interference in the sound receiver itself, masking the noise of the aircraft.

Apart from the above shortcomings, acoustics were hampered by a fundamental physical problem: the low speed of sound in air. Because of this, the sound detector would direct anti-aircraft guns to a point past which the high-speed aircraft had already passed. Under such conditions, it was difficult to illuminate the target with searchlights and engage it with fire. For typical aircraft speeds, sound detection allowed only a few minutes to take countermeasures.

With the approach of World War II, radar became an alternative to acoustic detection of aircraft. A radar system, as we know, consists of an electromagnetic wave generator (usually in the radio or microwave range), a transmitting/receiving antenna, and a signal processing unit. In active detection mode, radio waves are reflected from an object. The reflected signal carries information about the target location and speed.

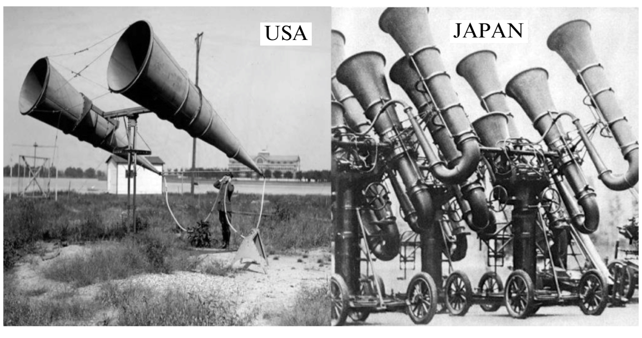


Figure 13. Foreign examples of sound-catching stations.

Radars were developed for military use before the onset of and during World War II. Magnetrons came to be the primary generator. However, mass production of radars became possible only after the war.

So, radars and sonars have their advantages and disadvantages. At present, acoustic technology has been largely forced out, but is experiencing a renaissance. The military role of stealthy and low-altitude targets (cruise missiles, drones, helicopters, small aircraft) is growing, so the development of acoustic systems will become increasingly topical.

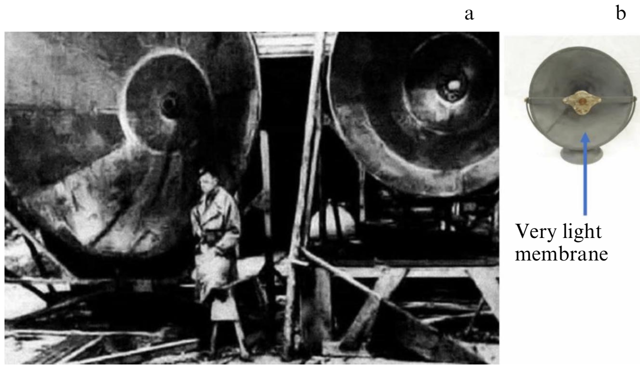


Figure. 14. Acoustic cannon (a) and old loudspeaker (b).

The above applies to weak (linear) sound in air. The media are prone to discuss the topic of 'acoustic weapons.' This is not a new topic, but it still entertains the laity. It would suffice to recall the 'Trumpets of Jericho,' which destroyed fortress walls, or Grigorii Adamov's novel, *The Mystery of Two Oceans,* in which ultrasonic guns kill a sperm whale and produce a channel for a submarine trapped in ice. Students of acoustics know this is impossible. The higher the intensity of periodic acoustic waves, the stronger their attenuation (this is a saturation effect). As a result, energy sufficient to destroy a target cannot be transmitted over significant distances. This is possible only at ranges of tens of centimeters.

However, talk of acoustic weapons is not without merit. Such systems must periodically emit single pulses (produce a sequence of microexplosions). German engineers made the greatest progress. During the war, Germany developed (in 1944) the 'Schallkanone' emitter (Fig. 14), capable of causing concussion. Mounted at the center of a parabolic reflector 3 meters in diameter was an injector with an ignition system fed with oxygen and methane. The explosive mixture was ignited at regular intervals, producing a continuous roar of the desired frequency. It is well known that exciting intense sound in air necessitates large amplitudes of velocity fluctuations (not pressure, as in a condensed medium). Thus, the vibrating membrane of old loudspeakers (Fig. 14b) was made of paper. The Germans went further. In their acoustic cannon, the shock wave front played the role of a very light membrane.

At present, the possibility of developing new supersonic passenger aircraft (instead of the Tu-144) is under discussion again. It is well known that the main problem is the unacceptably high level of sonic boom, which has a harmful effect on people and animals [7]. Recall that lift at supersonic speeds is produced by the 'rebound' of the emitted wave on the aircraft's fuselage and wings. If the sonic boom could be somehow suppressed, the aircraft would not fly. An example is the aerodynamic profile of the 'Adolf Busemann biplane,' which, when flown around something, does not produce a sonic boom, but produces no lift.

It is well known that acoustic wave emission weakens as the aircraft elongates, inversely proportionally to the fourth power of its length. There is no way to significantly elongate the profile using a 'needle' fairing. Bending vibrations (flutter) occur, and the fairing breaks off. Rem Viktorovich Khokhlov examined the possibility of profile elongation using an intense laser beam directed forward [22]. Unfortunately, atmospheric absorption of existing laser radiation is insufficiently high to effectively elongate the profile. Changing the aerodynamics will also achieve little: increased fuel consumption will presumably raise the already high costs of supersonic aviation.

Figure 15. M-25 'Hellish Mower' designed by Vladimir Mikhailovich Myasishchev (a) and shock wave from supersonic fighter jet flying at low altitude (b).

But the opposite phenomenon — an increase in the 'strength' of a sonic boom — is technically quite feasible. The idea was first conceived by aircraft designer Vladimir Mikhailovich Myasishchev. His supersonic aircraft, the 'Hellish Mower' (Fig. 15), was designed to inflict mass casualties on enemy infantry when flying at a low altitude. At an altitude of 50 m, the excess pressure in the shock wave could amount to 0.22 kG cm^{-2}. The ledge under the fuselage was deployed in combat mode. However, such an acoustic weapon is obviously not very effective. It is known that the destructive power of an explosion depends nonlinearly on the TNT equivalent; it is often assumed to be a cube root. This means that increasing the equivalent by 27 times will increase the explosion's impact only three-fold. Therefore, instead of the giant M-25, it would be more expedient to use a squadron of small supersonic fighters arranged in a phased antenna array.

In conclusion, we mention parametric loudspeakers designed by analogy with hydroacoustics (see Section 3). They are used in the air to directionally transmit signals in the audible frequency range using small ultrasonic emitters. It is also possible to make individual receivers (headphones) containing highly nonlinear elements. By directing a modulated ultrasonic wave at such a receiver, one can implement 'prompting' — the covert transmission of messages to a desired person. Such screens — 'tour guides' — have already been made for museums. Approaching an exhibit, a person receives audio information about it, although this information is available only within a small domain near the object [23].

5. Medical applications

Military acoustics fostered the development of ultrasound technology and its use in medicine. Austrian psychiatrist Karl Theodore Dussik is believed to be the first physician to use ultrasound for diagnostic purposes. He visualized brain tumors using an ultrasound device in 1942 [24]. Apparently, his work was significantly influenced by Soviet physicist and Corresponding Member of the USSR Academy of Sciences Sergei Yakovlevich Sokolov. He is the inventor of 'sound vision' [25] and the recipient of two Stalin Prizes (in 1942 for the invention of ultrasonic flaw detection and in 1951 for the invention of the ultrasonic microscope and the industrial development of acoustic flaw detection techniques).

These were the first steps. In the post-war years, medical acoustics began to develop rapidly. According to 1998 data, X-ray equipment led the global market in sales volume, followed by magnetic resonance imaging (MRI) and ultrasound diagnostic devices (USDs). However, in recent years, X-ray equipment has significantly lost ground (due to potential health risks), while ultrasound and MRI have surged ahead. Today, acoustic devices occupy a leading position on the global market both in sales volume and in the number of units produced. They significantly outperform laser and nuclear diagnostic devices. Diagnostic ultrasound sonographs are available in virtually all medical institutions. All of the above applies to diagnostics. If we move on to therapeutic and surgical applications, intense sound is required.

The American Fry brothers, Bill and Frank, are recognized as pioneers in the medical use of intense acoustic waves. In 1946, they set up a bioacoustics laboratory at the University of Illinois. Their goal was to make ultrasound equipment and develop surgical procedures for the brain. Prior to this, Frank had worked on the Manhattan Project, and Bill had worked in theoretical physics and the development of sonar systems. In 1957, surgeon Meyers and the brothers successfully performed the first ultrasonic surgery on a human brain. They treated Parkinson's disease by destroying specific areas of the brain using ultrasound.

Far less is known about the similar work of our compatriot, the outstanding engineer and Corresponding

Figure 16. Charles-Edouard Le Corbusier (left), Sergei Mikhailovich Eizenshtein (center), and Andrei Konstantinovich Burov (right), 1927.

Figure 17. Some of the building constructed according to designs of Andrei Konstantinovich Burov. (a) First panel building in USSR: 'delicate' house near Dynamo metro station. (b) Building in the central part of Moscow.

Member of the Academy of Architecture Andrei Konstantinovich Burov (father of Professor V.A. Burov). According to many people familiar with his work, Andrei Konstantinovich Burov can be put on a par with engineering geniuses of the rank of Vladimir Grigor'evich Shukhov. Here are some of A.K. Burov's achievements.

(1) Andrei Konstantinovich Burov (Fig. 16) was the founder of industrial panel housing (along with Le Corbusier), which involved manufacturing panels in a factory and assembling them on-site. The first such building was the 'delicate' house in Moscow at the intersection of Begovaya Street and Leningradskii Prospekt. It was built in 1939–1940, long before the mass construction of 'Khrushchev-era' apartment buildings.

(2) He designed several famous buildings in Moscow and was one of the originators of a new architectural style. These buildings are located in the central part of Moscow and can still be seen today (Fig. 17).

(3) In the invention of lightweight construction materials, Burov developed a series of new fiberglass-type composites reinforced with glass fibers.

(4) In 1947, in the pre-laser era, he developed optical fibers for image transmission and a technology for producing high-quality quartz filaments. He proposed encoding images by cutting a bundle of fibers and rotating it by a certain angle. Almost no one knows about this work, even experts in fiber optics.

(5) Burov developed US sources with record-breaking (and still unrivaled) characteristics [26].

(6) During ultrasound irradiation of malignant tumors, A.K. Burov observed the disappearance of metastases. Almost nothing is known about this either. Information was obtained from A.K. Burov's notes and photographs, as well as from reminiscences of his colleagues who survived into the early 2000s.

The experiments were performed at the Laboratory of Anisotropic Structures (LAS) of the USSR Academy of Sciences, founded by A.K. Burov. Setting up the LAS was discussed at the highest level: at a Politburo meeting. The decision to establish the laboratory was personally signed by Iosif Vissarionovich Stalin.

The LAS, which operated from 1950 to 1957 (until Burov's death), essentially originated new scientific areas: nonlinear and biomedical acoustics. Renowned scientists worked at the LAS: Sergei Aleksandrovich Akhmanov, Vladimir Aleksandrovich Krasil'nikov, and Lev Konstantinovich Zarembo, as did eminent physicians, biologists, and engineers. Yurii Isaakovich Kitaigorodskii developed 100-kV radio generators in the 350-kHz — 2-MHz range. The transducers were natural quartz plates up to 12 cm in diameter. Acoustic intensities of 500 W cm^{-2} were achieved in parallel unfocused beams. This record still stands, as the piezoceramics used today crack under such loads (Fig. 18).

Clinical trials were conducted jointly with future academician Nikolai Nikolaevich Blokhin at the Institute of Experimental Pathology and Cancer Therapy (later transformed into the Oncology Center). Twelve patients with terminal melanoma volunteered. Complete disappearance of metastases was observed in half of the patients; the rest died. The result was many times greater than the probability of spontaneous healing (Fig. 19).

A possible explanation for this effect was provided in Ref. [27]. It is related to both physics and biology. Our molecular biologist Aleksei Matveevich Olovnikov established the critical role of the telomerase enzyme in the development of the immune response to malignant cells. It is well known that normal cells can divide from 50–70 times (a young organism) to 20–30 times (at the age of about 70). With each division, the length of the telomeric ends of DNA

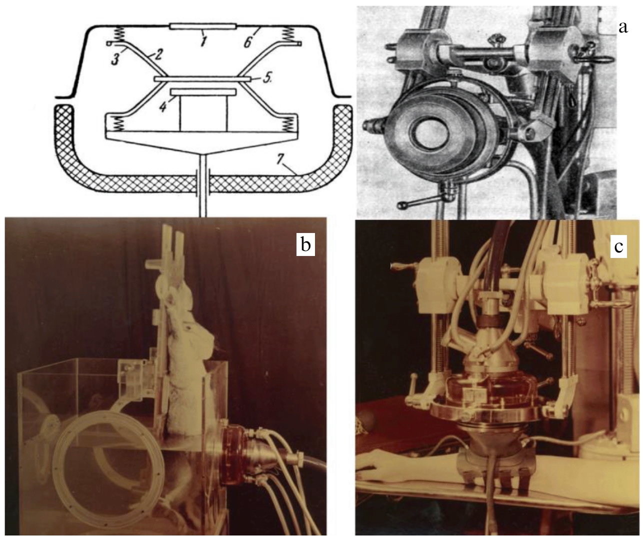


Figure 18. Design of high-power ultrasonic emitter (a). Irradiation of tumor in rabbit testicle (b) and on human arm (c).

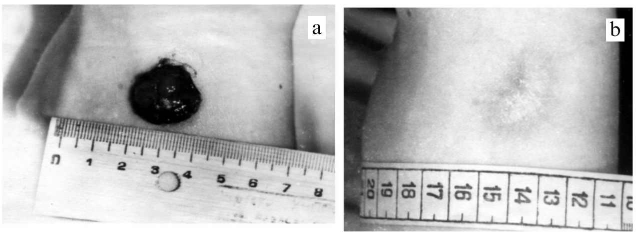


Figure 19. Primary melanoblastoma on patient's hand prior to (a) and after (b) high-intensity ultrasound irradiation.

shortens. After reaching the 'Hayflick limit,' the cell becomes decrepit, stops dividing, and dies. By contrast, cancer cells are 'immortal,' because the ends of their DNA are protected by special protein structures called telomeres. The synthesis of telomere structures occurs under the action of telomerase, while in normal cells this enzyme is inactive.

The authors of Ref. [27] hypothesized that telomerase is released from malignant cells after their nonthermal destruction by a series of weak shock waves of nonlinear ultrasound. The released enzyme stimulates the immune response. T-lymphocytes destroy malignant cells. This hypothesis is borne out by the effectiveness of an autovaccine tested at the LAS in 1956. Homogenized and irradiated with nonlinear ultrasound, the tumor mass was centrifuged, and the liquid portion was administered to the same sick animal. After a few days, the malignant process was suppressed in 40–80% of cases. However, if the solid (sedimentary) portion was administered, tumor growth, on the contrary, was enhanced. Histological studies of irradiated cells showed that changes in the cells were strongly pronounced when the source was located at distances of about 2–3 lengths of the shock formation in the US wave [27]. It was precisely this irradiation mode that was used in A.K. Burov's work.

So, in 1971, Aleksei Matveevich Olovnikov explained the 'Hayflick limit': the finite number of divisions a cell can undergo. He pointed to the role of the telomerase enzyme, which prevents the shortening of the telomeric ends of chromosomes with each replication. It is pertinent to quote Hayflick himself: "Olovnikov's insightful suggestion received experimental confirmation" in the work of Carolyn Widney Greider and Elizabeth Helen Blackburn, who received the 2009 Nobel Prize in Physiology and Medicine for this. According to Academician Vladimir Petrovich Skulachev, "This is highly unfair...." As a 'consolation,' Olovnikov was awarded the Demidov Prize.

The mechanisms by which high-intensity acoustic waves affect biological tissue are highly diverse. Among them is the noninvasive destruction of bioconcretions by shock pulses. The development of domestic lithotripters was first identified in 1983 due to the risk of renal colic in pilots and cosmonauts experiencing significant G-forces. Shock fronts of nonlinear waves generate large pressure gradients capable of destroying contrast targets (stones, bones, or lung tissue).

Nonlinear absorption at the shock front is an order of magnitude stronger than conventional absorption of an acoustic wave; such radiation can therefore be used to rapidly heat tissue and produce high radiation-induced forces. Non-invasive ultrasound heating can save a patient's life after a car accident or on the battlefield, when internal bleeding must be stopped and emergency hospitalization is not possible; more than half of such patients typically die. Ultrasound ablation is used in prostate surgery. Histotripsy, a nonthermal tissue ablation technology, is rapidly gaining ground, for example, to reduce tumor volume.

High radiation pressure helps 'force' fragments of broken stones out of the renal pelvis and urinary tract. Modulated radiation pressure is also used in a new diagnostic device, the elastograph, which has already enjoyed wide clinical use. The elastograph measures the most informative parameter for detecting tumors, scars, and hematomas: the shear modulus. This is by no means a complete list of the current problems of military medical acoustics.

It is worth noting that the year 2001 saw the foundation of the International Society for Therapeutic Ultrasound (ISTU). The organization brings together physicists, biologists, physicians, and engineers working with high-intensity focused ultrasound (HIFU). One of the society's areas of work — ultrasound stimulation of the immune system — effectively continues the development of the ideas and results described above. Medical technologies tested by A.K. Burov are employed in clinical practice in a number of countries.

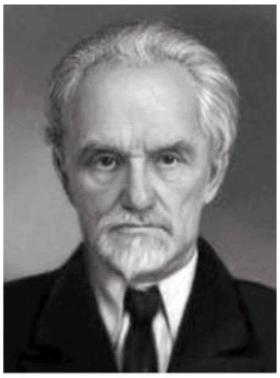
The development of other applications of acoustics historically associated with the activities of scientists and engineers during the war years is partially reflected in review Ref. [28].

6. Conclusions

Many scientists who engaged in fundamental physical problems made significant contributions to the development of applied acoustics. Among them are renowned physicists and academicians Nikolai Nikolaevich Andreev, Leonid Maksimovich Brekhovskikh, Vladimir Iosifovich Veksler, Evgenii L'vovich Feinberg, Aleksandr Aleksandrovich Kharkevich, and corresponding members Dmitrii Ivanovich Blokhintsev and Sergei Yakovlevich Sokolov.

Figure 20 shows portraits of only a few of the outstanding 'acoustic long-livers.' First, there are two scientists who are often referred to as the founders of Soviet acoustics: Academician Nikolai Nikolaevich Andreev, founder of the Acoustics Institute [29], and Sergei Nikolaevich Rzhevkin, founder of the Chair of Acoustics at Moscow State University [30]. Yurii Mikhailovich Sukharevskii is known as an outstanding pianist, but for 50 years he was also the main consultant and designer of underwater sonars (USSR State Prize) [31]. On his 90th birthday, he uttered a memorable phrase: "For 50 years I could not publish anything, and I read banal articles by other authors with humor." Vitalii Anatol'evich Zverev [32] was a renowned specialist in the field of radiophysics, acoustics, radar, and holography. He was a corresponding member of the Russian Academy of Sciences, laureate of the USSR State Prize. In particular, Zverev invented parametric sonar [33]. Lev Sergeevich Termen is probably the most famous acoustician, a man with an amazing biography. He was a laureate of the Stalin Prize. Universally known among his unclassified results is the world's first electronic musical instrument, the theremin [34]. Vladimir Aleksandrovich Krasil'nikov is the founder of nonlinear acoustics. He was a laureate of the State Prize, the M.V. Lomonosov Prize, and the L.I. Mandel'shtam Prize [35, 36].

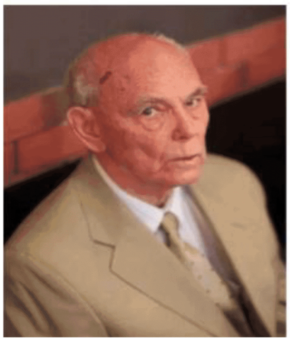
The most important results of Soviet acousticians obtained by the mid-1940s are described in review [37]. An example of modern applied research in the field of hydroacoustics is associated with the mastering of the Arctic sea shelf [38] and the development of large-aperture parametric antennas [39].



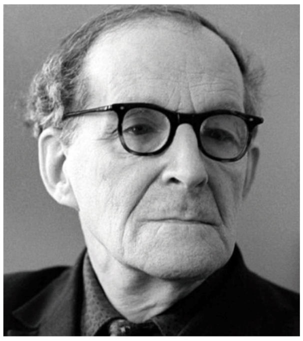
Nikolai Nikolaevich Andreev (1880–1970)

Sergei Nikolaevich Rzhevkin (1891–1981)

Yurii Mikhailovich Sukharevskii (1906–2004)



Vitalii Anatol'evich Zverev (1924–2024)



Lev Sergeevich Termen (1896–1993)

Vladimir Aleksandrovich Krasil'nikov (1912–2000)

Figure 20. Some outstanding 'long-livers' of domestic acoustics.

The names of other scientists, as well as the numerous engineers who designed unique acoustic systems, cannot be mentioned within the scope of this brief review. Their contribution to victory was invaluable. Furthermore, the successes in the development of domestic science and technology in the post-war years are undoubtedly based to a large measure on the selfless work of many of our compatriots aimed at solving defense problems during the war.

Information on all authors who published in the *Acoustic Journal* can be found on the website www.akzh.ru, in the '03. Personalities' section. The site was made under the direction of V.G. Shamaev and is openly accessible [40].

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