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Ultrasonic Gravitational Wave Detector and the Results of its Application

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ABSTRACT
A new physical phenomenon has been established: the influence of gravitational fields on propagating acoustic and ultrasonic waves. Based on this, a new promising gravitational wave detector has been developed and successfully tested. For this purpose, two independent measurement channels with acoustically transparent media were created, in which ultrasonic waves propagate in mutually opposite directions. By creating certain physical conditions, ultrasonic waves are brought into a state of test bodies, continuously suspended in acoustically transparent media. The created test bodies, in the form of ultrasonic waves, are subjected to the influence of gravitational waves during their propagation. Through differential measurement of the mutual oscillations of ultrasonic waves that have passed through acoustically transparent media in mutually opposite directions, gravitational waves are reliably detected directly. The developed ultrasonic detector allows for continuous observation of numerous gravitational waves not only from our Galaxy, but also from the Universe. Gravitational explosions of supernovae are practically continuously observed from various directions in space. Through narrow-band frequency filtering, gravitational signals from neutron star pulsars can be distinguished from among tens of millions. Gravitational signals of unknown nature are also observed. The detector allows selective listening to gravitational waves in the audible frequency range. The operation of the detector provides evidence of the enormous speed of gravitational wave propagation compared to the speed of light. The importance of the obtained results lies in their fundamental nature, due to the direct detection method underlying the detector's operation. This creates competition and a serious alternative to expensive projects for creating gravitational observatories based on laser interferometric observation methods.

Keywords: detector, gravitational waves, supernova stars, neutron stars, speed of gravity.

INTRODUCTION
At present, the most popular technology in observational astronomy is gravitational astronomy. In the course of research in this direction, the author has experimentally established a new physical phenomenon: the influence of gravitational fields on acoustic and ultrasonic waves of finite amplitude propagating in acoustically transparent media [1-2]. The phenomenon consists in the acceleration and deceleration of the speed of acoustic and ultrasonic waves depending on whether they propagate along or against the direction of the gravitational field intensity vector. The concept of acceleration and deceleration of their

propagation speed becomes applicable to acoustic and ultrasonic waves in the literal physical sense of the term. Previously, such definitions and concepts did not exist, were not used, and were not encountered in physical acoustics [3]. The positive properties of this phenomenon are that, under certain propagation conditions, ultrasonic waves actually represent a continuous flow of test bodies constantly suspended in gravitational fields. On this basis, ultrasonic waves are recognized as a perfect mechanism for the free fall of bodies, whose vibrations can be continuously measured and recorded as an ideal process for detecting gravitational waves.

Based on the above, an ultrasonic technology has been developed that allows the registration of gravitational waves coming from surrounding space [4-6]. Gravitational oscillations and waves from many stars, including neutron star pulsars, are registered in the frequency range from fractions of a hertz to tens of kilohertz. Oscillations of neutron star pulsars, as well as gravitational explosions of supernovae, are recorded in real time. Gravitational glitches of some neutron stars have also been detected, consisting of a sharp multiple increase in the intensity of their gravitational oscillations [5, 6]. However, further research suggests that the nature of glitches is most likely caused by a newly discovered phenomenon: interstellar gravitational-wave resonance, which requires further investigation. The detector allows selective listening to gravitational waves in the audible frequency range. An important result of the detector's operation is evidence of the enormous speed of gravitational wave propagation compared to the speed of light. This article is devoted to these studies, new experimental results, and the analysis of their reliability.

PHYSICAL PRINCIPLES OF THE ULTRASONIC GRAVITATIONAL WAVE DETECTOR

The operating principle of the ultrasonic detector is based on a new physical phenomenon: the influence of gravity (gravitational force) on the propagation of ultrasonic waves. The physical essence of the influence of gravity on the propagation of acoustic or ultrasonic waves is that, in a propagating wave of finite amplitude, due to nonlinearity, an excess density associated with the wave arises. In turn, the appearance of excess density is equivalent to excess mass, which in a gravitational field generates a force associated with the propagation of the acoustic or ultrasonic wave. The resulting force causes a change in the speed of ultrasound propagation depending on the direction and magnitude of the external acceleration. In turn, the external acceleration is a gravitational wave, so the described mechanism underlies the method for detecting gravitational waves.

Let us derive the wave equation describing the process of propagation of an acoustic (ultrasonic) wave, taking into account the medium's nonlinearity and gravity. To simplify the derivation, we will make the following permissible assumptions:

The acoustic (ultrasonic) wave is one-dimensional and propagates vertically in a medium located in a uniform gravitational field;

1. The medium is an ideal gas (liquid), for which $\boldsymbol{\chi} = \mathbf{c_p}/\mathbf{c_\vartheta} = \mathbf{const}$, where: $\boldsymbol{\chi}$ - is the ratio of specific heats at constant pressure and volume, neglecting dissipative processes;
2. The desired expression is a closed partial differential wave equation for displacements $\boldsymbol{\xi}(\boldsymbol{x}, \boldsymbol{t})$, with nonlinearity limited to quadratic terms.

Consider the motion of a small elementary volume of ideal gas $\boldsymbol{v}$, surrounded by a closed surface $\boldsymbol{S}$. Two types of forces act upon it: surface forces and body forces. The former (pressure forces) are determined by the interaction emanating from the particles of the medium lying outside the surface $\boldsymbol{S}$ and are applied to the surface particles of the volume $\boldsymbol{v}$. The resultant pressure ($\boldsymbol{p}$) force $\boldsymbol{F_1}$ over the surface can be written as:

$$F_1 = -\int_S p\,\mathrm{dS}. \tag{1}$$

The minus sign arises because the pressure force is directed opposite to the outward normal vector of the surface $\boldsymbol{S}$. According to the Ostrogradsky-Gauss theorem, the surface integral (1) can be replaced by a volume integral:

$$\int_\mathrm{S} \mathrm{pdS} = \int_\mathrm{v} \nabla\mathrm{pdv}, \tag{2}$$

where: $\boldsymbol{\nabla p}$ pressure ($\boldsymbol{p}$) gradient.

In addition to pressure forces, the volume element $\mathbf{dv}$ is subjected to gravity $\boldsymbol{\rho g d v}$. The resultant gravitational force $\boldsymbol{F_2}$ acting on the elementary volume is:

$$F_2 = \int_v \rho g dv \tag{3}$$

Thus, the resultant of surface and body forces acting on an elementary volume of gas is equal to the sum of the two equations above, (2) and (3):

$$F = F_1 + F_2 = -\int_v \nabla p dv + \int_v \rho g dv. \tag{4}$$

Within a small elementary volume $\boldsymbol{v}$, assuming the density and pressure gradient are constant, the mass of the volume can be expressed as: $\boldsymbol{m} = \boldsymbol{\rho v}$. In this case, equation (4), considering vector notation, is successively transformed into the following form:

$$\begin{gathered}\bar{F} = -\int_v \bar{\nabla} p dv + \int_v \rho \bar{g} dv = -\bar{\nabla} p v + \rho \bar{g} v;\\ m\bar{W} = \bar{F} = \rho v \bar{W} = -\bar{\nabla} p v + \rho \bar{g} v;\\ \rho \bar{W} = -\bar{\nabla} P + \rho \bar{g}.\end{gathered} \tag{5}$$

The resulting equation (5) represents the equation of motion for a non-viscous, non-heat-conducting gas (or liquid) and describes the conservation of mass and the adiabatic condition. Orienting the coordinate along the vertical axis, denoting the coordinate of the equilibrium position of the elementary volume of the medium as $\boldsymbol{x}$, and $\boldsymbol{X}$ - its coordinate at time as $\boldsymbol{t}$, we introduce a displacement field according to the following relation:

$$X(x,t) = x + \xi(x,t). \tag{6}$$

According to definition (6), equation (5) yields:

$$W_x = \frac{1}{\rho}\left(\frac{\partial P}{\partial x}\right)_t + g_x. \tag{7}$$

Here, $\boldsymbol{W_x}$ is the projection of the acceleration vector of the elementary volume $\boldsymbol{W}$ onto the direction $\boldsymbol{x}$ of wave propagation, and $\boldsymbol{g_x = -g}$ is the projection of the acceleration due to gravity onto the same direction $\boldsymbol{x}$.

To proceed from equation (7) to a closed-form wave equation for displacements $\boldsymbol{\xi(x,t)}$, it is expedient to perform the following:

1. Based on (6), one can define and write the partial derivatives for the vector projection:

$$W_x = \left(\frac{\partial^2 X}{\partial t^2}\right)_x = \left(\frac{\partial^2 \xi}{\partial t^2}\right)_x \equiv \ddot{\xi}. \tag{8}$$

2. From the law of mass conservation, it follows that the mass of gas enclosed within an elementary volume remains constant during the transition from time $\boldsymbol{t_0}$ to time $\boldsymbol{t}$:

$$\int_{\tau_0} \rho_0 dx = \int_{\tau} \rho dx. \tag{9}$$

where: $\boldsymbol{\rho_0 = \rho(x, t_0)}$; $\boldsymbol{\rho = \rho(X, t)}$.
Based on this, we can write:

$$\rho_0 dx = \rho dX = \rho\left(\frac{\partial X}{\partial x}\right)_t dx, \tag{10}$$

where: $\boldsymbol{\rho_0(x)}$ - is the gas density at equilibrium.
Based on (10), the following equivalent expression is valid:

$$\frac{1}{\rho}\left(\frac{\partial P}{\partial X}\right)_t = \frac{1}{\rho_0}\left(\frac{\partial P}{\partial x}\right)_t. \tag{11}$$

3. The adiabatic equation of state of the gas [7], taking into account expressions (10) and (6), can be represented in the form of a Taylor series expansion:

$$P = P_0\left(\frac{\rho}{\rho_0}\right)^{\gamma} = P_0\left(\frac{\partial X}{\partial x}\right)_t^{-\gamma} = P_0(1+\xi')^{-\gamma}$$
$$= P_0\left[1 - \gamma\xi' + \frac{\gamma(\gamma+1)}{2}\,\xi'.\xi' - \cdots\right] \tag{12}$$

where: $\xi' = (\partial\xi/\partial x)_t$, $P_0\ (x)$ - equilibrium pressure; γ - nonlinearity parameter.

4. The equilibrium pressure $\boldsymbol{P_0(x)}$ and equilibrium density $\boldsymbol{\rho_0(x)}$ are related by the condition of mechanical and acoustic equilibrium:

$$\frac{dP_0(x)}{dx} = \rho_0(x) \cdot g_x. \tag{13}$$

Substituting expressions (8), (11), as well as three terms from (12) into equation (7), after relatively simple transformations taking into account (13), we obtain the intermediate expression:

$$\rho_0 \frac{\partial^2 \xi}{\partial t^2} = -\frac{\partial P}{\partial x} + g(\rho + \Delta\rho), \tag{14}$$

where: $\boldsymbol{g\Delta\rho}$ - represents an additional force equal to the product of the excess mass (generated by excess density) and the acceleration due to gravity.

In reference [7], an equation was derived that relates the total pressure to the pressure in the unperturbed state, which can be expressed as:

$$P = P_0 \left(\frac{1}{1 + \frac{\partial \xi}{\partial x}} \right)^{\gamma}.$$

Based on this equation, we find the partial derivative $\frac{\partial P}{\partial x}$:

$$\frac{\partial P}{\partial x} = -\gamma P_0 \left(1 + \frac{\partial \xi}{\partial x}\right)^{-\gamma-1} \cdot \frac{\partial^2 \xi}{\partial x^2}. \tag{15}$$

Equation (15) is exact, as it takes into account terms of second and higher orders of smallness. Substituting (15) into (14), we obtain:

$$\rho_0 \frac{\partial^2 \xi}{\partial t^2} - g \cdot \Delta\rho = +\gamma P_0 \frac{\frac{\partial^2 \xi}{\partial x^2}}{\left(1 + \frac{\partial \xi}{\partial x}\right)^{\gamma+1}};.$$

$$\frac{\partial^2 \xi}{\partial t^2} - g \frac{\Delta\rho}{\rho_0} = \frac{\gamma P}{\rho_0} \cdot \frac{\frac{\partial^2 \xi}{\partial x^2}}{\left(1+\frac{\partial \xi}{\partial x}\right)^{\gamma+1}}. \tag{16}$$

However, $\frac{\Delta\rho}{\rho_0} = -\gamma \frac{\partial \xi}{\partial x}$, and $\frac{\gamma P_0}{\rho_0} = c_0^2$. Therefore, as a result of successive transformations, we obtain the final equation:

$$\frac{\partial^2 \xi}{\partial t^2} + \gamma g \frac{\partial \xi}{\partial x} = c^2 \frac{\frac{\partial^2 \xi}{\partial x^2}}{\left(1+\frac{\partial \xi}{\partial x}\right)^{\gamma+1}}. \tag{17}$$

Expression (17) is an exact equation describing the nonlinear propagation of acoustic waves under the influence of gravitational fields. It is advisable to perform some additional transformations:

$$\left[\frac{\partial^2\xi}{\partial t^2}+\gamma g\frac{\partial\xi}{\partial x}\right]\cdot\left(1+\frac{\partial\xi}{\partial}\right)^{\gamma+1}=c^2\frac{\partial^2\xi}{\partial x^2};.$$

$$\left[\frac{\partial^2\xi}{\partial t^2}+\gamma g\frac{\partial\xi}{\partial x}\right]\cdot\left[1+(\gamma+1)\cdot\frac{\partial\xi}{\partial x}+\frac{(\gamma+1)\gamma}{2}\left(\frac{\partial\xi}{\partial x}\right)^2+\ldots\right]=c^2\frac{\partial^2\xi}{\partial x^2}. \quad (17')$$

We neglect the squared terms, since the square of the derivative $\left(\frac{\partial\xi}{\partial x}\right)^2$ is of second order smallness; then, successively, we obtain:

$$\frac{\partial^2\xi}{\partial t^2}+\gamma g\frac{\partial\xi}{\partial x}+(\gamma+1)\cdot\frac{\partial\xi}{\partial x}\frac{\partial^2\xi}{\partial t^2}+(\gamma+1)\gamma g\left(\frac{\partial\xi}{\partial x}\right)^2=c^2\frac{\partial^2\xi}{\partial x^2};.$$

$$\frac{\partial^2\xi}{\partial t^2}\left[1+(\gamma+1)\frac{\partial\xi}{\partial x}\right]+\gamma g\frac{\partial\xi}{\partial x}=c^2\frac{\partial^2\xi}{\partial x^2}. \quad (18)$$

The obtained wave differential equation (18) accurately describes the processes of propagation of finite-amplitude acoustic waves in a nonlinear medium under the influence of a gravitational field. The validity of the derived equation is confirmed by the fact that, in the first approximation, the nonlinear wave equation (18) coincides with the equation presented in [8], which was obtained there as a special case of wave equations for media with an arbitrary equation of state. It should also be noted that the wave equation (18) reduces to the known relations in equation [8], when nonlinearity is "turned off," and to the well-known equation [9], when gravity is "turned off." Furthermore, when both nonlinearity and gravity are simultaneously "turned off," equation (18) with sufficient accuracy reduces to the standard wave equation [3], well known in acoustics. Thus, equation (18) should be considered reliably justified.

An exact solution of the obtained nonlinear differential equation is possible by reducing it to quasilinear systems.

To this end, let us consider equation (18) in its most convenient form:

$$\frac{\partial^2\xi}{\partial t^2}+(\gamma+1)\frac{\partial\xi}{\partial x}\frac{\partial^2\xi}{\partial t^2}+\gamma g\frac{\partial\xi}{\partial x}=c^2\frac{\partial^2\xi}{\partial x^2}. \quad (19)$$

Let us introduce new functions:

$$V=\frac{\partial\xi}{\partial x}, U=\frac{\partial\xi}{\partial t} \quad (20)$$

Then, from (19) and (20), we obtain a system of quasilinear equations:

$$\left.\begin{array}{c}\frac{\partial V}{\partial t}-\frac{\partial U}{\partial x}=0\,;,\\ \frac{\partial U}{\partial t}+(\gamma+1)V\cdot\frac{\partial U}{\partial t}+\gamma gV-c^2\frac{\partial V}{\partial x}=0.\end{array}\right\} \quad (21)$$

By means of justified mathematical transformations, it is possible to obtain a solution to the system of quasilinear equations (21), which has the form:

$$x_1 = ct\left(1 - \frac{A}{2}\right) - \frac{\gamma A}{4} g t^2, \tag{22}$$

$$x_2 = -ct\left(1 - \frac{A}{2}\right) - \frac{\gamma A}{4} g t^2, \tag{23}$$

where:

- $\boldsymbol{x_1}$ — the wave propagation equation in one direction;
- $\mathbf{x_2}$ — the wave propagation equation in the other direction;
- $\boldsymbol{A = \gamma(\gamma + 1)W}$ — the nonlinearity parameter related to the absolute value of the amplitude $\boldsymbol{W}$ of the ultrasonic wave.

Based on the fact that the obtained solutions (22) and (23) of the original wave equation (19) are valid for both constant and alternating values of the acceleration due to gravity, the practical application of the formula for calculating the alternating value of $\boldsymbol{g_{\sim}}$ was justified in scientific article [6]:

$$g_{\sim} = \frac{16L(T_2 - T_1)}{\gamma A (T_1 + T_2)^3}, \tag{24}$$

where: $\boldsymbol{g_{\sim}}$ is the alternating value of the acceleration due to gravity, proportional to the alternating influence of gravitational waves; $(\boldsymbol{T_2 - T_1})$ — the difference in the propagation times of ultrasonic waves caused by the direct effect of gravitational waves on the acoustic medium.

Thus, based on the analysis of gravitational effects on propagating ultraacoustic waves, the calculation formula (24) was obtained, which forms the basis for the operation of the gravitational wave detector.

STRUCTURAL DIAGRAM AND OPERATING PROCEDURE OF THE ULTRASONIC GRAVITATIONAL WAVE DETECTOR

The gravitational wave detector features a differential measurement scheme consisting of two ultrasonic measurement channels, UMC-1 (upper channel) and UMC-2 (lower channel), arranged facing each other and separated by acoustically transparent media (see Figure 1). It should be noted that this design is simpler, more advanced, and more reliable compared to the structural diagram presented in article [10]. One measurement channel, UMC-1, is oriented in one measurement direction in space, while the second channel, UMC-2, is oriented in the opposite direction. The operation of the detector's signals is ensured by a highly stable reference generator (RG), which generates synchronized excitation signals. These signals are sent through buffer amplifier BA-2 to the upper measurement channel UMC-1, and simultaneously through buffer amplifier BA-1 to the lower measurement channel UMC-2.

The upper channel UMC-1 includes the assembly of the first ultrasonic chamber, consisting of an acoustically coupled emitting ultrasonic transducer UT-11, the first acoustically transparent medium, and a receiving ultrasonic transducer UT-12. The lower channel UMC-2 is constructed similarly, comprising an emitting ultrasonic transducer UT-21, the second acoustically transparent medium, and a receiving ultrasonic transducer UT-22.

The differential measurement scheme is implemented by two identical, oppositely directed upper (UMC-1) and lower (UMC-2) acoustic measurement channels. The received ultrasonic signals from these channels are fed through low-noise preamplifiers P-1 and P-2 to a synchronous detector (SD). This circuit design and the differential measurement method provide maximum sensitivity to gravitational accelerations. The signals from the outputs of the receiving ultrasonic transducers UT-12 and UT-22 are delivered to different inputs of the synchronous detector SD via low-noise preamplifiers P-1 and P-2, which increases noise immunity.

The resulting signals, as a result of gravitational wave detection, are output from the synchronous detector (SD) and sent to the signal processing unit (SPU). The SPU includes a low-noise amplifier, a spectrum analyzer, analog and digital filters, an information processing and accumulation unit, as well as a timer and a control unit. Depending on the type of measurement, either spectral analysis or filtering is used, and most often a combination of both. The obtained results are sent to a personal computer (PC) for long-term storage. Signals are also sent from a separate output of the signal processing unit to a speaker. This technical solution makes it possible to qualitatively listen to the gravitational signals from the selected cosmic source. For spatial scanning, which is necessary for detecting and receiving gravitational waves from various vector directions in space, the entire assembly of primary ultrasonic transducers is mounted on the horizontal platform of a rotary device of the system (RDS). This allows the ultrasonic measurement channels UMC-1 and UMC-2 to be freely rotated and positioned 360° in the horizontal plane and up to 45° in the vertical plane.

An important design feature is the implementation of various protective measures against external influences such as vibrational, acoustic, and even ultrasonic interference [6,10]. The fundamental circuit solutions are designed to ensure minimal noise parameters in combination with achieving the maximum signal-to-noise ratio during the processing of received signals. A specific acoustic medium has been selected, maintaining the required internal pressure and temperature, which ensures the stability of the nonlinearity parameter $\boldsymbol{A}$, thereby providing long-term measurement stability in accordance with formulas (22-24). Electronic components with the lowest permissible noise levels are also used, ensuring that the equivalent noise of the detector, referred to the input, does not exceed 2×10^{-9} V per square root Hertz, i.e., 2 nV/√Hz. One of the important results of the improved gravitational wave detector's operation is the frequency resolution of the received signals, which, at its limit, is no worse than 10 microhertz (1×10^{-5} Hz). A distinctive feature of the detector is also the complete electrical shielding of the equipment from external electrical, electromagnetic, and magnetic interference. This is achieved by using internal battery power for all units.

The sensitivity of the developed ultrasonic detector for measuring gravitational alternating accelerations is no worse than one ten-millionth of a meter per second squared (10^{-7} m/s^2) in the frequency band from 0.5 Hz to 1 kHz. In the extended frequency band up to 20 kHz, the sensitivity is no worse than one millionth of a meter per second squared. Such sensitivity parameters are achieved with an average signal accumulation and processing time of no more than one to two seconds, while maintaining long-term measurement stability over many hours.

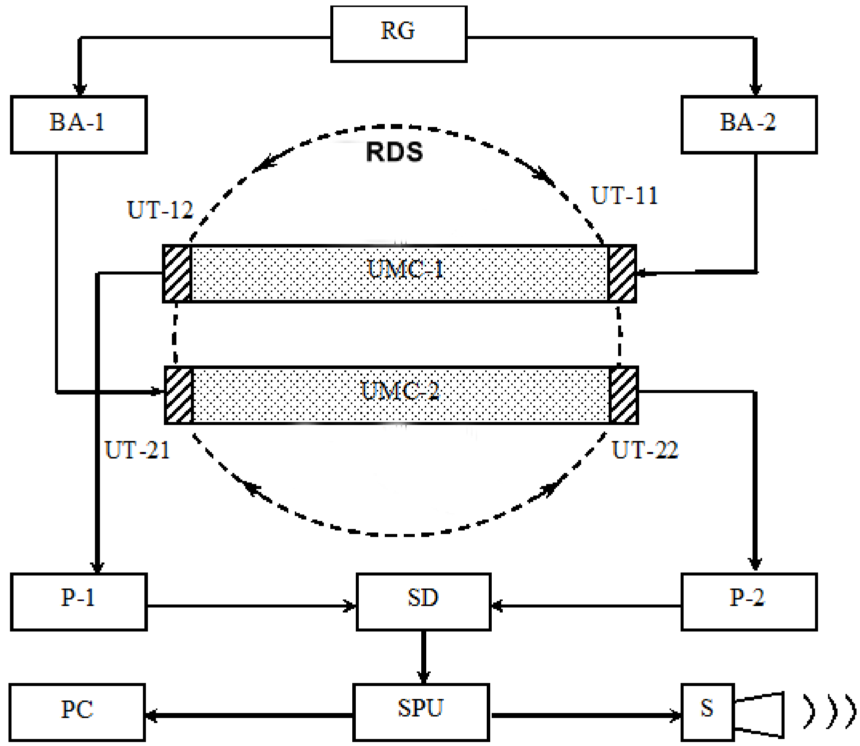

Figure 1: Block diagram of the gravitational wave detector. RG – reference generator; BA-1, BA-2 – buffer amplifiers; UT-11, UT-12, UT-21, UT-22 – ultrasonic transducers; UMC-1, UMC-2 – ultrasonic measurement channels with acoustically transparent media; RDS – rotation device of the setup; P-1, P-2 – preamplifiers; SD – synchronous detector; SPU – signal processing unit; PC – personal computer; S – speaker (loudspeaker)

MAIN EXPERIMENTAL RESULTS

Detection of Gravitational Waves Caused by Supernova Explosion

Over several years of observations, at least five gravitational supernova explosions have been recorded almost daily. This is the first important result from the experimental data, which can be observed at any time during the detector operation. Three drawings were selected from numerous spectrograms showing the development of a gravitational supernova explosion with an interval of 15 minutes.

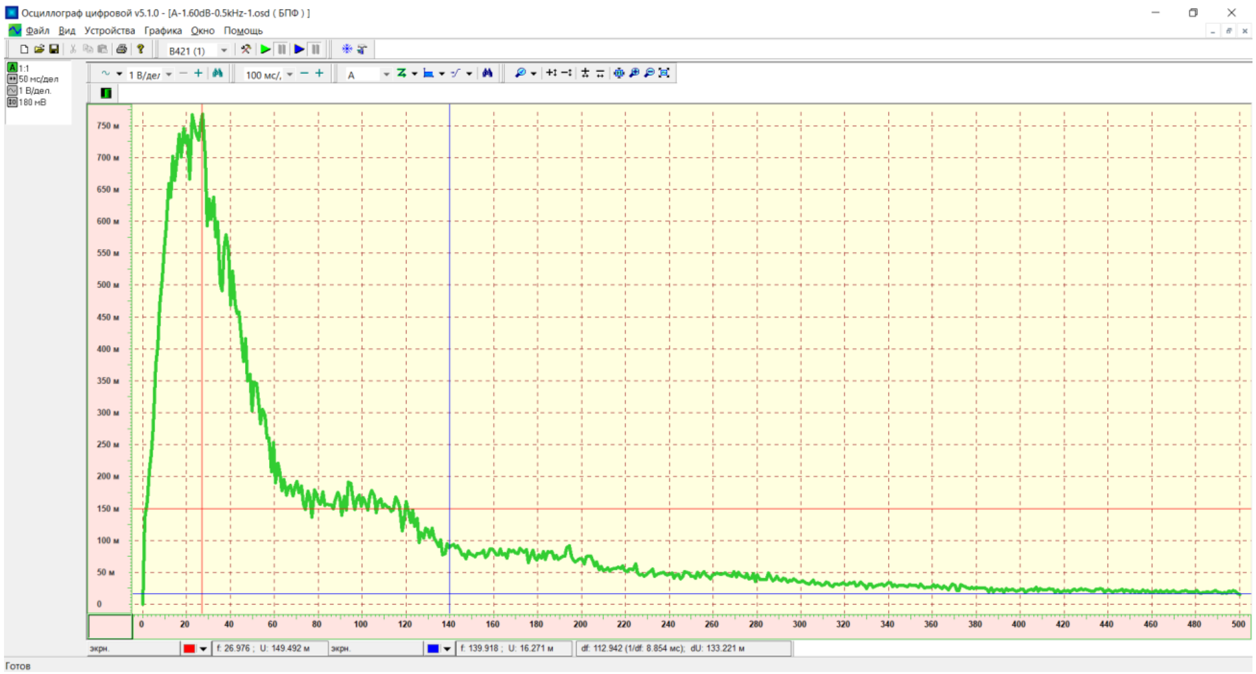

Figure 2: Spectrogram of gravitational signals from a supernova explosion, obtained 15 minutes after the start of the explosion. To achieve a measurement response time of no worse than 0.1 seconds, the spectrogram was recorded in the standard frequency resolution mode of 1 Hz (one hertz).

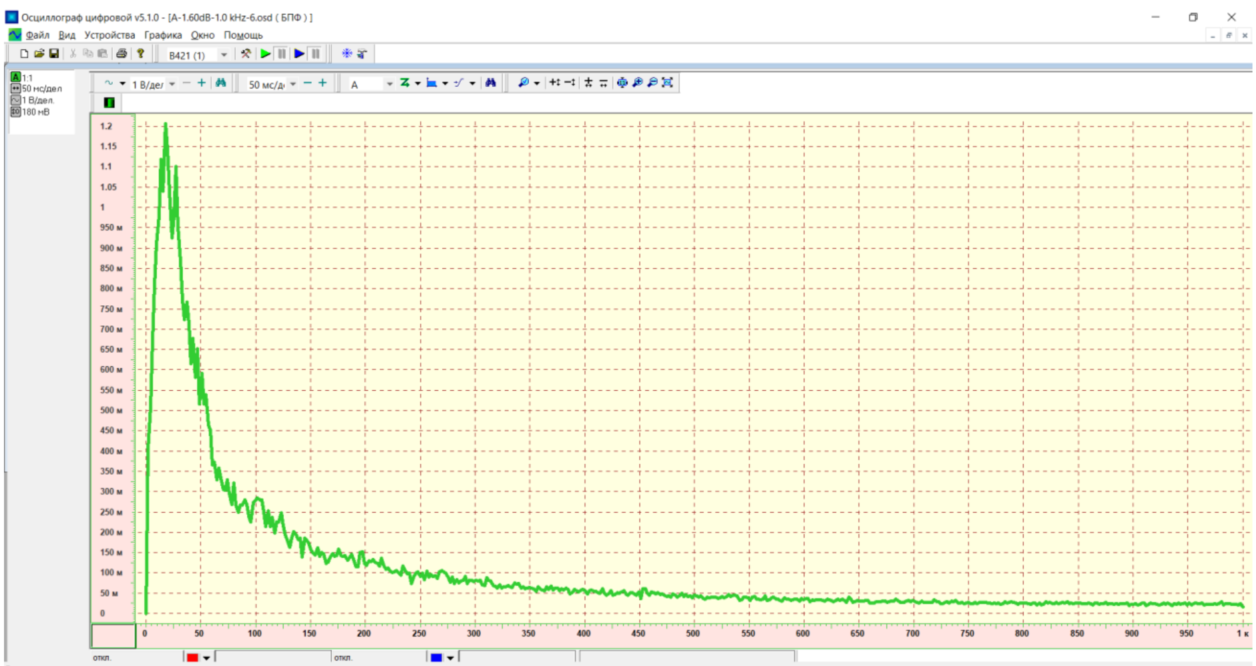

Figure 3: Spectrogram of gravitational signals from a supernova explosion, obtained 30 minutes after the start of the explosion, which corresponds to 15 minutes after the spectrogram in Figure 2. To achieve a measurement response time of no worse than 0.1 seconds, the spectrogram was recorded in the standard frequency resolution mode of 1 Hz (one hertz).

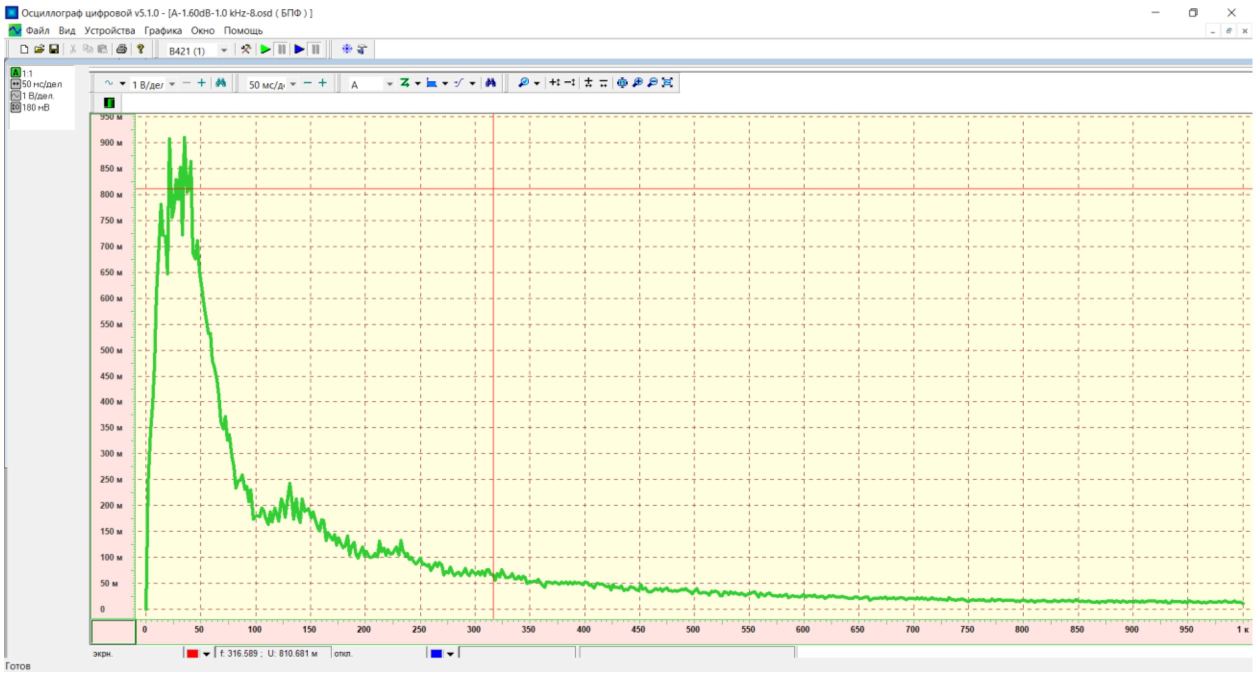

Figure 4: Spectrogram of gravitational signals from a supernova explosion, obtained 45 minutes after the start of the explosion, which corresponds to 15 minutes after the spectrogram in Figure 3. To achieve a measurement response time of no worse than 0.1 seconds, the spectrogram was also recorded in the standard frequency resolution mode of 1 Hz (one hertz).

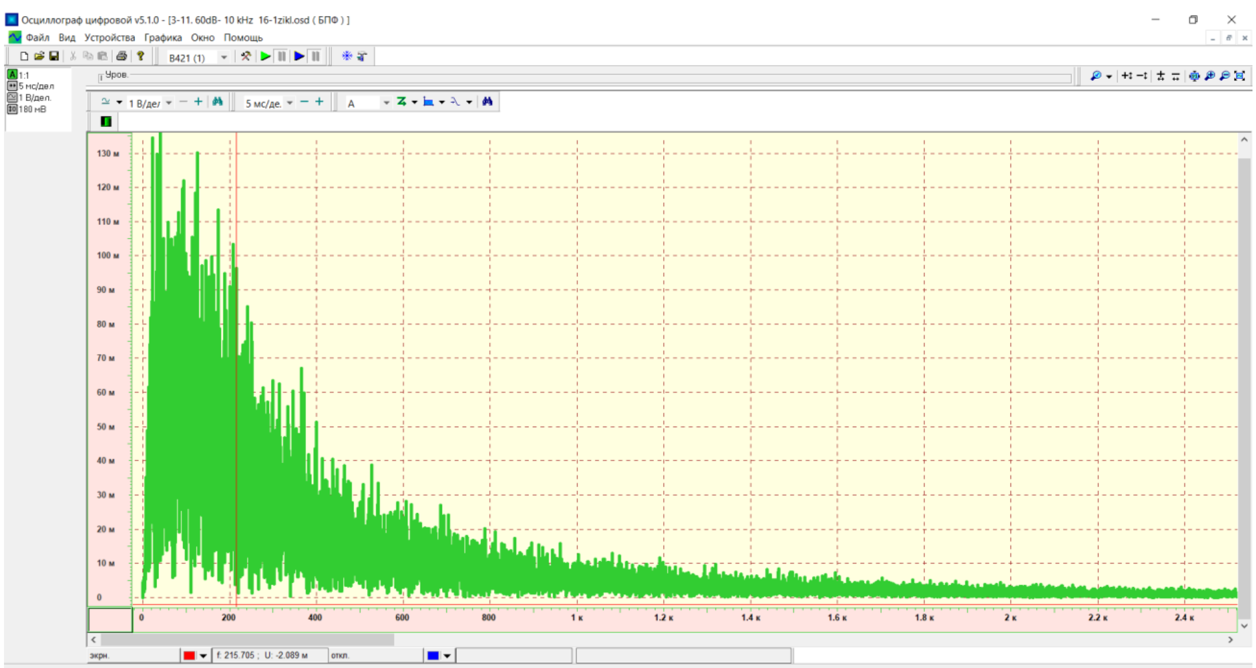

Figure 5: Spectrogram of gravitational signals from a supernova explosion, obtained three days after the start of the explosion. To examine the details, the spectrogram was recorded in a high-frequency resolution mode of 30 mHz (thirty millihertz).

Figure 5 displays the spectrogram of gravitational signals from a supernova explosion, recorded three days after the explosion began. To examine the details, the spectrogram in Figure 5 was obtained in a high-frequency resolution mode of 30 mHz (thirty millihertz). Based on the appearance of the spectrograms, it can be concluded that the main part of the gravitational oscillations caused by supernova explosions lies in the frequency range from zero to several kilohertz. It can be assumed — and most likely, this is the case — that the development of gravitational signals caused by supernova explosions is a broadband and evenly distributed process, characteristic of symmetric stars. Explosions of such stars result in matter being ejected uniformly in all directions; therefore, gravitational disturbances also propagate uniformly in all directions [6]. Due to the different directions of the uniformly ejected mass, the resulting gravitational waves have equal but oppositely directed phase components. As a result, the superposition of gravitational disturbances partially cancels out, and the resulting gravitational waves do not have high intensity. In the case of an asymmetric, predominantly one-sided supernova explosion, opposing regions of matter — unevenly distributed on different sides of the star — fly apart with different accelerations. Therefore, such a supernova explosion generates a differential gravitational wave with a sufficiently high amplitude. A crucial point here is that there is no complete mutual cancellation of gravitational signals, resulting in a frequency difference in the frequency spectrum of the supernova explosion. This differential gravitational frequency is mainly concentrated in the low-frequency range. Since most supernova explosions are asymmetric, such explosions generate gravitational waves with a low-frequency spectrum, which are registered by the ultrasonic detector and shown in Figures 2–4.

Nevertheless, it is important to emphasize the significance of the obtained gravitational measurements. The presented gravitational spectra make it possible to study the emergence, development, and dynamics of the processes accompanying supernova explosions. At the same time, rapid measurements can be carried out.

Determination and Estimation of the Propagation Speed of Gravitational Waves

The second, no less important, result of the gravitational wave detector's operation is the determination of the speed at which gravitational waves propagate. According to preliminary results and calculations, the ultrasonic detector makes it possible to detect, in various vector directions of space, at least several tens of millions of gravitational signals from neutron star pulsars in the frequency range up to 20 kHz. When observing gravitational waves emitted by neutron star pulsars with the detector, it was found — by comparing their gravitational and electromagnetic frequencies — that there is a huge difference between the propagation speeds of gravitational and electromagnetic waves [4]. To determine this difference, studies were conducted by comparing the received gravitational signals with data from the Australian Astronomical Observatory, which has an extensive catalog of electromagnetic observations of numerous neutron star pulsars [11]. In these studies, the main frequencies of gravitational and electromagnetic oscillations were compared first and foremost. Experimental results showed that each neutron star pulsar emits its main gravitational energy at the fundamental resonance frequency, which coincides with the frequency of optical radiation. This made it possible to obtain objective results. In article [6], with regard to neutron star pulsars, an iterative algorithm of successive approximations was proposed for determining the propagation speed of gravitational waves. The essence of this iterative algorithm is as follows. According to the astronomical catalog [11], the first neutron star pulsar is selected, having a small time derivative of frequency F1 relative to the main barycentric rotation frequency F0. The combination of a small time derivative of frequency F1 and a small distance from the pulsar to Earth gives a relatively small difference between the gravitational and electromagnetic frequencies. This difference ensures the unambiguity of measurements, as it does not exceed one period of the measured signals. Based on the obtained data, the first approximate value of the gravitational wave propagation speed is calculated and determined. This is the first step in implementing the measurement algorithm.

Next, according to the astronomical catalog [11], a second neutron star pulsar is selected, having an average time derivative of frequency F1 relative to the main barycentric rotation frequency F0. The increased derivative provides a somewhat larger difference between the gravitational and electromagnetic frequencies. When performing calculations, it is necessary to take into account the distance to the neutron star pulsar. The resulting difference may be ambiguous, as it can exceed one period of the measured signals. To eliminate ambiguity, the correction obtained above in the first step of the preliminary approximate determination of the gravitational wave propagation speed is applied. Based on the obtained data, the second, more accurate value of the gravitational wave propagation speed is calculated and determined. This is the second step in implementing the measurement algorithm. Then, according to the astronomical catalog [11], a third neutron star pulsar is selected, having a large time derivative of frequency F1 relative to the main barycentric rotation frequency F0. The large derivative provides a greater difference between the gravitational and electromagnetic frequencies, which allows for a more precise determination of the gravitational wave propagation speed. When performing calculations, it is also necessary to take into account the distance to the neutron star pulsar. The resulting difference is ambiguous, as it exceeds one period of the measured signals. To eliminate ambiguity, the correction obtained above in the second step of the more accurate determination of the gravitational wave propagation speed is applied. Based on the obtained data, the third, refined value of the gravitational wave propagation speed is calculated and determined.

Thus, three equations are compiled, each containing the relationship between the gravitational and electromagnetic frequencies of oscillations of different neutron star pulsars located at various distances from Earth. By introducing into these equations the parameters of the distances, the parameters of the pulsars' rotational slowdown, the intermediate results for the actual frequencies of gravitational oscillations of the pulsars, as well as by calculating the difference between the frequencies of gravitational and electromagnetic oscillations, it becomes possible to sequentially solve these equations and determine a refined value for the speed of propagation of gravitational waves.

Let us consider an example of determining the propagation speed of gravitational waves. To simplify the calculations, we will start from the second step of the above-described method. We will perform the calculation for pulsar **B0355+54** [11]. The pulsar parameters according to the ATNF Pulsar Catalogue are as follows:

1. No. 2466 in the catalog: B0355+54.
2. F0 = 6.3945110925 Hz – barycentric rotation frequency (Hz).

3. F1 = -17.9709E-14 – time derivative of the barycentric rotation frequency (spin-down rate in Hz per second).
4. F2 = 4.10E-25 – second time derivative of the barycentric rotation frequency (rate of change of spin-down in Hz per second squared).
5. Dist = 1.000 kpc = 1000 pc = 1000 × 3.2616 = 3261.6 light-years.
   Dist = 3261.6 × 365 days × 24 hours × 3600 seconds = 102,857,817,600 seconds (light travel time).
6. ΔF1 = F2 × Dist = 4.10E-25 × 102,857,817,600 s = 4.2171705216E-14 (magnitude of the change in spin-down rate in Hz per second).
7. Adjusted F1 = F1 + ΔF1 =-17.9709E-14 + 4.2171705216E-14 = -13.7537294784E-14 (total derivative of the change in spin-down rate in Hz per second).
8. ΔF = F1 × Dist = -13.7537294784E-14 × 102,857,817,600 s = -0.01414678598009 Hz (change in spin-down in Hz).
9. Adjusted F0 = F0 + ΔF = 6.3945110925 – 0.01414678598009 = 6.380364306519 Hz (adjusted gravitational oscillation frequency of the neutron star pulsar).

Let us use Figure 6 to measure the gravitational frequency **FG** of oscillations of the neutron star pulsar. For this, we take into account the approximate value of the gravitational wave propagation speed obtained in the first step of the iteration. This value defines a zone of result exclusion, extending leftward from the frequency **F0** by an amount proportional to the speed of gravity as determined in the first iteration step. Based on this, the specific real gravitational signal according to Figure 6 is: **FG = 6.3797 Hz.** Multiplying the ratio of the difference between the barycentric rotation frequency F0 and the adjusted frequency F0adj by the absolute difference between the measured gravitational frequency FG and the adjusted frequency F0adj by the propagation velocity of optical waves, we determine the propagation velocity of gravitational waves:

$$\text{Sgrav} = (\text{F0} - \text{F0adj}) / (\text{FG} - \text{F0adj}) \times \text{Sopt}. \quad (25)$$

By substituting the specific values into formula (25), we obtain the result that the speed of propagation of gravitational waves exceeds the speed of propagation of optical waves by no less than **21** (twenty-one) times.

We proceed to the third step of the study, in which a third neutron star pulsar is selected, having a large time derivative F1 of the main barycentric rotation frequency F0. The chosen pulsar is B0833-45 [11]:

1. No. 2580 in the catalog: B0833-45.
2. F0 = 11.1946499395 Hz — barycentric rotation frequency (Hz).
3. F1 = -1.5666E-11 — time derivative of the barycentric rotation frequency (spin-down rate in Hz per second).
4. F2 = 1.028E-21 — second time derivative of the barycentric rotation frequency (rate of change of spin-down in Hz per second squared).
5. Dist = 0.280 kpc = 280 pc = 280 × 3.2616 × 31.536E6 = 28.8002E9 seconds (light travel time).
6. ΔF1 = F2 × Dist = 1.028E-21 × 28.8002E9 s = 29.6E-13 (magnitude of the change in spin-down rate in Hz per second).

7. Adjusted F1 = F1 + ΔF1 = -1.5666E-11 + 29.6E-13 = -1.574598E-11 (total derivative of the change in spin-down rate in Hz per second).
8. ΔF = F1adj × Dist = -1.574598E-11 × 28.8002E9 s = -0.453488 Hz (change in spin-down in Hz).
9. Adjusted F0 = F0 + ΔF = 11.1946499395 Hz – 0.453488 Hz = 10.741162 Hz (adjusted gravitational oscillation frequency of the neutron star pulsar).

As previously noted, the large derivative F1 provides a greater difference between the gravitational and optical frequencies, which allows for a more precise determination of the gravitational wave propagation speed. We take into account the approximate value of the gravitational wave propagation speed obtained in the second iteration step. To do this, we divide the frequency ΔF = 0.453488 Hz (change in spin-down) by the number of times that the speed of gravitational waves exceeds the speed of optical waves as obtained in the second step. The resulting value Δ(ΔF) = 0.021595 Hz, when added to the adjusted gravitational oscillation frequency F0 of the neutron star pulsar, defines the boundary of the result exclusion zone F=10.762 Hz on the side of higher frequencies, which are to the left of the barycentric rotation frequency F0 (see Figure 7). Measurements are made by referencing the nearest gravitational signal between the adjusted gravitational oscillation frequency F0 and the exclusion boundary Δ(ΔF) on the side of higher frequencies.

Figure 6: Spectrogram of gravitational signals near the neutron star pulsar B0355+54, with a main barycentric rotation frequency F0 = 6.3945110925 Hz, adjusted F0 = F0 + ΔF = 6.380364306519 Hz, and a measured gravitational frequency FG = 6.3797 Hz.

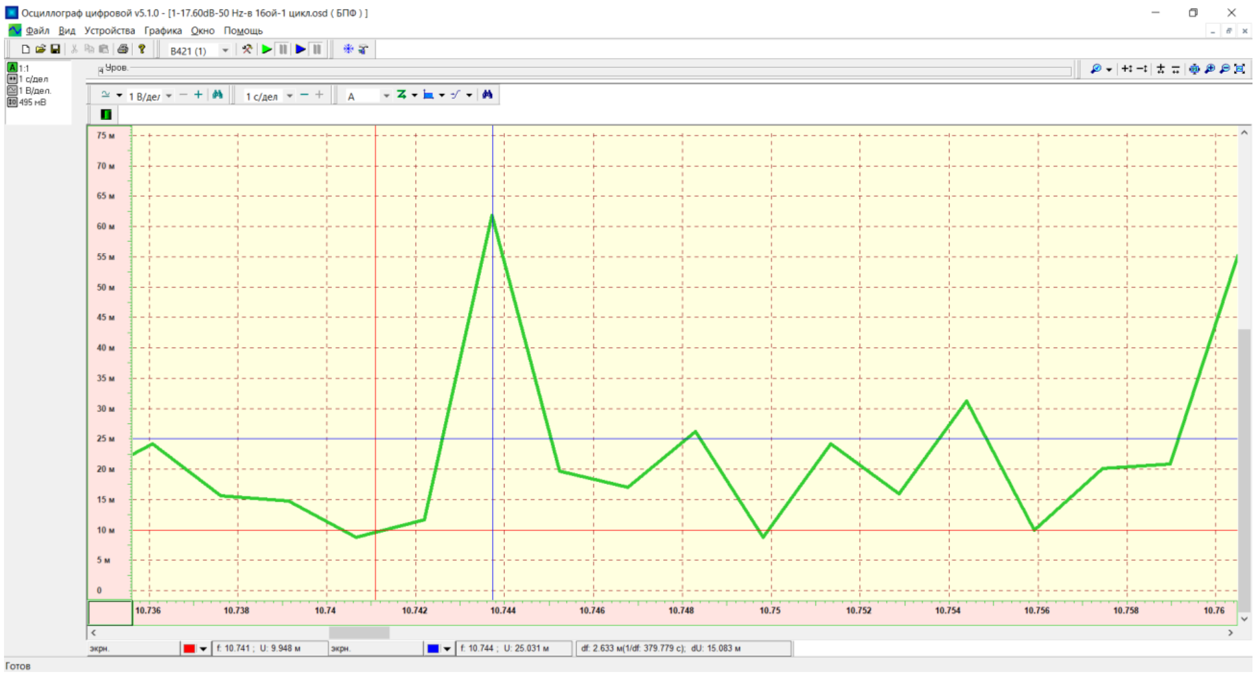

Figure 7: Spectrogram of gravitational signals near the neutron star pulsar B0833-45, with a main barycentric rotation frequency F0 = 11.1946499395 Hz, adjusted F0 = F0 + ΔF = 10.741162 Hz, and a measured gravitational frequency FG = 10.7437 Hz.

Thus, the gravitational oscillation frequency of the neutron star pulsar according to Figure 7 is: FG = 10.7437 Hz. Substituting the parameter values into formula (25), the result shows that the speed of propagation of gravitational waves exceeds the speed of propagation of optical waves by no less than 178.7 times and is 53.6589 million kilometers per second, that is, approximately 54 million kilometers per second. To summarize the above, it should be noted that, in order to refine the obtained result for the speed of propagation of gravitational waves, it is advisable to use a high-speed spectrum analyzer with high frequency resolution in the detector.

ADVANTAGES OF THE ULTRASONIC GRAVITATIONAL WAVE DETECTOR

The ultrasonic gravitational wave detector has the significant advantage of allowing for the direct and immediate detection and measurement of any alternating accelerations propagating through space in any direction. Gravitational waves, as a physical phenomenon, are local alternating accelerations that propagate rapidly through space. The detector implements a direct method of physical measurement and does not impose any restrictions on the propagation speed of gravitational waves.

In contrast, it should be noted that the observatories created by the LIGO, VIRGO, and KAGRA collaborations [12–14] fundamentally rely on an indirect method of physical measurement for the detection and observation of gravitational waves. The physical principle underlying the operation of LIGO, VIRGO, and KAGRA observatories is based on measuring the deformation of objects under the influence of gravitational waves. In this case, the measurement system is connected to objects that are simultaneously in a state of inertial rest and are also linked to the surrounding structure, which characterizes the indirect measurement method. In contrast, the ultrasonic detector organizes the measurement of fluctuations of freely falling ultrasonic waves, which, in their physical nature, are equivalent to freely falling bodies, thus providing a direct method for detecting gravitational waves.

Therefore, there is a fundamental difference in the physical principles of operation between the ultrasonic detector and the known observatories. In the created observatories, under the influence of an incoming gravitational wave, local tidal accelerations should cause a difference in the applied forces along the length of the measurement baseline. However, all objects and components of the measurement baseline, including the interferometric system with its reflecting mirrors, possess inertia. In reality, there is static inertial resistance to any applied force, including alternating and extremely small forces; this property can be called inertial resistance. Consequently, the well-known method underlying the operation of the LIGO, VIRGO, and KAGRA observatories is based on the expected changes in the inertial resistance of each part of the measurement system due to tidal accelerations caused by gravitational waves [13,14]. However, precisely because of the method of expected changes in the inertial resistance of the measurement system, the known gravitational observatories have relatively low sensitivity [15,16].

The second problem encountered by gravitational observatories in achieving sufficiently high sensitivity to gravitational waves is related to the speed of gravitational wave propagation. It is correct to recognize the fact of the enormous propagation speed of gravitational waves, which is many times greater than the speed of light. This is demonstrated above in section **4.2**. In this case, the entire measurement system, including the sensors, measurement channels, base, platform, installation, etc.—that is, all the "physical infrastructure"—will "fall" in the gravitational field of the wave in the same way everywhere, and no changes in inertial resistance will arise along the length of the measurement baseline, including in the interferometric measurement system. Thus, due to the enormous speed of gravitational wave propagation, the entire structure of the measurement system is affected in phase, resulting in compensation of the expected results. This, as well as the inertial resistance of the measurement system to incoming gravitational waves, are the main problems faced by existing gravitational observatories in achieving sufficiently high sensitivity for gravitational wave detection [17]. It is worth emphasizing once again that in the developed ultrasonic detector, the propagating ultrasonic waves freely fall in acoustically transparent media under the influence of alternating gravitational effects. In this case, the propagating ultrasonic waves represent a continuous stream of test bodies, constantly suspended in gravitational fields.

Therefore, ultrasonic waves actually represent an ideal mechanism of freely falling bodies, the fluctuations of which can be continuously measured and registered as the best process for receiving gravitational waves. Based on the described mechanism of gravity's influence on the speed of ultrasound propagation, it can be concluded that the ultrasonic detector implements a method of direct measurement. The operation of the detector also provides evidence for the enormous speed of gravitational wave propagation compared to the speed of light. The importance of the obtained results lies in their fundamental nature. Based on these results, it is advisable to abandon costly projects for the construction of gravitational observatories based on laser-interferometric observation methods.

CONCLUSIONS

1. A theoretical analysis was carried out of the previously discovered new physical phenomenon of the influence of gravitational fields on ultrasonic waves of finite amplitude propagating in acoustically transparent media.
2. A nonlinear wave differential equation was derived, describing the physical nature of the discovered phenomenon of gravity's effect on the propagation of acoustic waves. The equation was solved, and the operating formula for the ultrasonic gravitational wave detector was substantiated.
3. The ultrasonic technology and the detector developed on its basis represent a method and, accordingly, an instrument for direct measurements. The detector allows for the direct detection and measurement of accelerations propagating through space, which are gravitational waves, without additional conversions.
4. Estimates have shown that the sensitivity of the developed detector to gravitational waves in the frequency band from 0.5 Hz to 1.0 kHz is no worse than one ten-millionth of a meter per second squared. In a broader frequency band up to 20.0 kHz, the detector's sensitivity is no worse than one millionth of a meter per second squared.
5. One of the important results of the improved gravitational wave detector's operation is the frequency resolution of the received signals, which is, at best, no worse than 10 microhertz (1×10^{-5} Hz). This enables the detection of a huge number of neutron star pulsars.
6. According to preliminary estimates, the ultrasonic detector makes it possible to detect, in various vector directions of space, at least several tens of millions of gravitational signals from neutron star pulsars in the frequency range up to 20 kHz.
7. The experimental results obtained unequivocally confirm that the developed ultrasonic detector allows for the continuous observation of numerous gravitational waves. The detector reliably detects gravitational signals from the Universe, in particular, supernova explosions, which are observed almost continuously.
8. The operation of the detector also provides evidence for the enormous speed of gravitational wave propagation compared to the speed of light. A fundamental result was obtained showing that the speed of propagation of gravitational waves exceeds the speed of propagation of optical waves by at least one hundred and seventy-eight times.
9. The detector allows for the selective isolation and high-quality real-time listening of gravitational oscillations in the audio frequency range.
10. The advantages and fundamental nature of the results obtained lie in the new possibilities and prospects for studying the Universe, as well as in the potential to abandon costly projects for the construction of gravitational observatories based on laser-interferometric observation methods.

SUMMARY

This work relates to new methods and instruments in observational astrophysics, particularly gravitational astrophysics. A new type of astronomical instrument has been developed: an ultrasonic gravitational wave detector. The operation of the detector is based on the nonlinear physical phenomenon of gravity's influence on ultrasonic waves propagating in acoustically transparent media. Due to this phenomenon, ultrasonic waves are directly affected by gravitational waves. The detector enables fundamentally new experimental results in the detection of gravitational waves.

With the developed ultrasonic detector, it is possible for the first time to continuously observe numerous gravitational waves from neutron star pulsars. Gravitational oscillations from neutron star pulsars are observed in quantities of at least several tens of millions. The detector reliably detects gravitational signals from the Universe, in particular, supernova explosions, which are observed almost continuously. The operation of the detector also provides evidence for the enormous speed of gravitational wave propagation compared to the speed of light. A fundamental result was obtained showing that the speed of propagation of gravitational waves exceeds the speed of propagation of optical waves by at least one hundred and seventy-eight times. The detector allows for the selective isolation of any gravitational signals and the ability to listen to them in the audio frequency range. Based on the results obtained, it can be assumed that gravitational signals from neutron star pulsars are detected at distances within our Galaxy, while supernova explosions are detected from stellar systems located tens or even hundreds of millions of light-years from Earth. It appears that the developed technology, in the form of the created gravitational wave detector, will be a worthy alternative to costly laser-interferometric gravitational observatory projects. It is also expected that this work will open new opportunities for exploring the Universe.

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