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# Gravitational wave experiments in Russia

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**Abstract. A brief summary is given of experimental research on the detection of extraterrestrial gravitational radiation performed in Russia since the late 1960s. Various aspects of this topic are reviewed, including experiments with resonant detectors, geophysical methods for detecting low-frequency gravitational waves, and high-frequency versions of the gravitational 'Hertz experiment'. A description is given of the current situation concerning the unique optoacoustic gravitational detector OGRAN mounted in the underground laboratory of the Baksan neutrino observatory, Institute for Nuclear Research, Russian Academy of Sciences. Prospects are examined for building a long-base gravitational wave interferometer in Russia that would be integrated into a global network of gravitational antennas.**

**Keywords:** gravitational wave experiment, gravitational wave detection, gravitation detectors

## 1. Introduction

The first detection of a gravitational wave signal from coalescing binary black holes with masses of about 30 solar masses at a distance of 400 Mpc is a remarkable discovery that confirmed the reality of hopes that gravitational wave (GW) astronomy can be a new unique channel of information about our Universe [1]. The dimensionless amplitude of the GW signal (the space metric variation in the geometric language) detected by LIGO (Laser Interferometer Gravitational Wave Observatory) was $h \approx 10^{-21}$ with a mean carrier frequency of 150 Hz.

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The signal waveform corresponded to a canonical chirp signal, a wave train with a changing carrier frequency and three characteristic phases: inspiral, merging, and ring-down. Before the end of 2016, two other signals with smaller amplitudes were registered [2]. Naturally, this achievement gave rise to a burst of activity of scientific collaborations and the individual scientific groups involved, who proposed new long-term projects of high-sensitivity detectors, such as the Einstein Telescope [3], Voyager, and Cosmic Endeavour [4].

The LIGO Scientific Collaboration (LSC) also included two Russian groups from Lomonosov Moscow State University (MSU) (V B Braginsky and his collaborators from the MSU Faculty of Physics) [5] and from the Institute of Applied Physics, RAS (Russian Academy of Sciences) [1] (A M Sergeev, E A Khasanov, et al.) [6], who have been responsible for separate functional units of the LIGO detectors, and they justly share in the general success.

In this paper, however, we would like to recall the history of the problem of searches for GWs from cosmic sources that started roughly 50 years ago and in which Russian science played a significant role at the initial stage. Here, the strong stimulating influence of the leading scientists of the Division of General Physics and Astronomy of the USSR Academy of Sciences (USSR AS) should be stressed (V L Ginzburg and Ya B Zel'dovich) and of the Division of Nuclear Physics of the USSR AS (A A Logunov and M A Markov), who were dedicated proponents and initiators of GW experiments. Thanks to the last two leaders, searches for experimental GW studies started at the Baksan Neutrino Observatory (BNO) of the Institute for Nuclear Research (INR), RAS in the northern Caucasus.

## 2. From predictions to experiment

After having predicted the existence of gravitational waves in [7], Einstein himself came to doubt the possibility of their experimental detection. His calculation of the simplest GW generator, a rotating rod, gave a tiny gravitational radiation

[1] Here and below, the current names of the institutions are given.

power: for a mass of 500 t, a length of 20 m, and a disruption-limited angular velocity $\omega \approx 30$ rad s$^{-1}$, the output GW power was $\sim 10^{-23}$ erg s$^{-1}$. This corresponded, according to the geometric interpretation of General Relativity (GR), to deviations of the flat metric by a relative value $h \sim 10^{-35}$. The possibility of constructing a laboratory detector to measure such a weak signal was ruled out a priori.

At the same time, this result stimulated the search for gravitational wave sources among relativistic objects with large masses, strong gravitational fields, and relativistic velocities during cosmic catastrophes. Correspondingly, the problem of registration of GW emission from such sources reduced to building sufficiently sensitive ground-based detectors (antennas).

The practical possibility of constructing such antennas appeared in the second half of the 20th century due to the rapid development of physical experimental technique, including the appearance of atomic frequency standards, the creation of instruments for precision radiophysical and optical measurements, space orbital apparatuses, their radio and optical ranging, etc.

The Soviet scientists started discussing the GW detection problem at around 1960. Since then, regular nation-wide gravitational conferences have been organized (initiated by the Council for Science and Technology of the USSR Ministry of High and Secondary Special Education), which seriously discussed this topic. The first conference met in the summer of 1961 at MSU; one of its principal organizers was a professor in the Faculty of Physics, D D Ivanenko. Before the conference, the book entitled *The Newest Problems of Gravitation* edited by Ivanenko [8] was published, which included the Russian translations of papers from the leading foreign journals, in particular, the papers by Bondi [9] and Weber [10].

In theoretical paper [9], Bondi (apparently for the first time) considered a GW receiver consisting of a pair of test masses connected by a spring, the so-called oscillating dumbbell, which later became the equivalent scheme (model) of all resonance solid GW detectors. This structure corresponds to the distinctive features of the GW action on surrounding bodies: its quadrupole (or tidal) character, a consequence of the equivalence principle underlying gravitation, as well as the absence of negative masses (gravitational repulsion).

In the original paper by Weber [10] (later his monograph [11] appeared), a theory of interaction of gravitational radiation with a resonance detector was presented, the response of the detector due to a monochromatic GW with a given amplitude was calculated, the practical impossibility of a laboratory Hertz experiment with a resonance (mechanical) receiver and transmitter (inverted detector) was shown, and a method for registration of a cosmic GW signal using the coincidence of outputs on spatially separated detectors was proposed.

At the same time, several papers appeared in Russia that proposed the electromagnetic principle of GW registration. In a paper by Gertsenstein and Pustovoit [12], an optical Michelson interferometer was considered as the GW detector. The main motivation of the authors of [12] was to increase the efficiency of interaction of a GW with the detector by substituting a nonrelativistic test mass — the mechanical oscillating Bondi–Weber dumbbell — with a relativistic object, namely, light in an optical interferometer. In radio physics, such an idea is known as the condition of coordination of a receiver with radiation (the requirement that the wavelength be commensurable with the effective size of the receiver). Weber's mechanical detector with laboratory sizes, clearly, was strongly mismatched with the gravitational wavelength in the kHz frequency range.

Using GR equations, the authors of [12] computed the output of an interferometer (change in the interferometer fringes) as an equivalent change in the optical refractive index of the medium (vacuum) in the interferometer arms. For gravitational radiation from binary stars, the effect is negligibly small. The authors of [12] could not objectively estimate the possibility of its detection due to insufficient development of precision optical measurements at that time.

Another remarkable contribution of Russian science was the paper by Gertsenstein [13] that considered resonance conversion of a traveling GW into an electromagnetic one in the presence of a constant magnetic field. This effect was immediately associated with the problem of registration of gravitational radiation from remote stars. A GW passing through the galactic magnetic field (interstellar medium) should generate, pull along, and continuously amplify a coherent electromagnetic wave, which could be detected by a sensitive electromagnetic detector (for example, by a radio telescope in the ultra-high frequency (UHF) range). Later, the paper by Zel'dovich [14] was published, devoted to the "inverse Gertsenstein effect," i.e., the generation of a GW by electromagnetic radiation in a strong magnetic field. Later, these papers allowed researchers to return to the laboratory Hertz experiment on new grounds (see Section 5 below).

Weber is also the author of the idea [8, 11] to use Earth as a resonance detector with quadrupole modes and the registration system based on the use of a distributed network of gravimeters and seismographs on Earth's surface. This is, of course, quite a different frequency range: the lowest quadrupole terrestrial mode has a period of about 54 min with a quality factor of $\approx 400$. With Weber's participation, a high-sensitivity gravimeter was constructed in this frequency range [15, 16], and the upper bound on the flux density of cosmic gravitational radiation of the order of $10^8$ erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$ at the frequency $\omega \sim 10^{-3}$ rad s$^{-1}$ was obtained [14], which was later revisited several times, including by Soviet researchers. This limit by itself was not too significant, because it greatly exceeded theoretical estimates of the expected gravitational radiation power from galactic binary stars.

A selective list of the most interesting binary stars in this respect was presented in Braginsky's review [17]. A more detailed analysis of gravitational radiation from galactic binary stars was later carried out by Mironovskii [18], revealing a spectral peak at the doubling orbital frequency of W Ursa Majoris (W UMa) stars (orbital period about 8 h). The spectral amplitude at the maximum reached $10^{-19}$ Hz$^{1/2}$ in terms of metric variations, or about $10^{-8}$ erg s$^{-1}$ cm$^{-2}$ in the energy spectral density on Earth.

The review by Braginsky [17] was in fact an informational proposal to organize a scientific group at the Faculty of Physics of MSU aimed at building ground-based GW detectors. In review [17], in particular, the idea was put forward (later developed in monograph [19]) that these should be parametric detectors with an external high-power pumping modulated by external (gravitational wave) perturbations. The response of such detectors to a GW can be much stronger than for passive transformers (without external pumping). The LIGO and Virgo laser interferometers are examples of such detectors.

## 3. Search for coincident signals

In 1968, in a sensational publication, Weber reported the observation of coincident pulses (excitations) on two resonance gravitational detectors [20], which were initially spatially separated by a relatively small distance (2 km) and later by the quite significant distance from Chicago to Maryland (about 1000 km). In Russia, it was Zel'dovich who immediately recognized the importance of these experiments and organized a meeting of his theoretical group at the Institute of Applied Mathematics (IAM RAS) with Braginsky's experimental group. According to Zel'dovich, this remarkable discovery could pave the way to a new information channel about the Universe, GW astronomy. Therefore, it would be necessary to become involved in this research from two angles: 1) to elaborate theoretical problems related to GW astronomy (GW sources and properties and the parameters of signals), and 2) to construct efficient ground-based GW detectors. The very first steps had to be analyzing and testing Weber's results. Here, Zel'dovich (as a rapid reaction) initiated the writing of a short paper [21], which, however, contained important conclusions affecting the later development of GW experiments (the term introduced to refer to all experiments on the search for GWs).

First, it was shown that the signals registered in Weber's experiments could not be due to the GW effect. Their amplitude and the rate of occurrence contradicted the lifetime of the Galaxy (and the Universe as a whole) by energy losses. A realistic source in the galactic center could produce metric variations at a level not exceeding $10^{-18}$, which appreciably contradicted the signal amplitudes reported by Weber, $10^{-16}$.

Second, the effective GW pulses could be produced only by relativistic (superdense) stars during the catastrophic moment of their formation: in supernova explosions, relativistic binary coalescences, and nonspherical collapses. The response of a resonance Weber detector to the typical signals [a short 'resonance train', a 'train with changing frequency' (chirp signal in the modern treatment), a 'video pulse' (with the duration equal to the carrier period)] was calculated in more detail in a subsequent paper [22], where the significant role of the high quality of the detector was also emphasized. The continuous signals could be produced by neutron stars (radio pulsars, which had just been discovered); however, the probability of their detection by Weber-type detectors was recognized to be low. The program of searches for extraterrestrial gravitational radiation was actually outlined in the early paper [22] and typical sources were pointed out, which remain relevant even now. Only one very ambitious area of current research, the detection of relic GW background from the Big Bang in the expanding Universe, similar to the cosmic microwave background but separated from the primeval plasma at a much earlier time, was not mentioned. But such a measurement could be hard to imagine at the relatively rough sensitivity level discussed at that time.

The small amplitude of the expected GW perturbations forced the use of optimal filtering methods — a field that had been already significantly developed by Russian science, with an extensive literature on radar location and long-distance space communication. This experience could be extended and applied to filtering GW signals. The first application was the recommendation for a Weber antenna to detect pulse perturbations with a duration much shorter than the detector relaxation time. The transition from measuring the response amplitude to measuring its derivative (or the 'differential link') is optimal, which was proposed in [23, 24]. In general, the choice of a specific filtering algorithm was theoretically determined by a priori information on the signal character. This stimulated studies of different model problems on astrophysical GW sources. In Zel'dovich's opinion, a model of the cluster of superdense objects (neutron stars or black holes) in the Galaxy center was plausible that enabled a detailed prognosis of the intensity, spectrum, and rate of the occurrence of GW bursts [25]. The time structure of the GW bursts (the pulse shape), in particular, was calculated in [26]. The known shape of the pulses enabled the matching filtering algorithm to be applied, which later became the leading algorithm in the analysis of GW signals from coalescing binary stars. At that time, all papers devoted to the data analysis from GW antennas referred to that algorithm as described in monograph [27] by Vainshtein and Zubakov.

At the end of the 1960s, Zel'dovich's group in IAM RAS continued active theoretical studies of astrophysical GW sources. The results presented an important estimate of the conversion efficiency (reaching 1%) of the rest-mass energy into gravitational radiation during a space catastrophe and were included in monograph [28]. Based on this estimate, one could formulate a general but sufficiently reliable prediction for the GW background from astrophysical GW bursts [29]. The amplitude of a short train of duration $\tau$ with a quasiresonance carrier frequency $\omega \sim \omega_0$ and a few oscillations, $\omega\tau \sim 1$, could be as high as $10^{-19}$ Hz$^{-1/2}$ with the probability of generation by a galactic center source $p \sim 10^{-2}$ (the probability of supernova explosions in the Galaxy), showing that such a train is quite a rare event. A more encouraging event rate, up to a few events per year, was predicted for GWs with a smaller amplitude, $h \simeq 10^{-21}$, from sources located at the Virgo cluster distance, $\sim 15$ Mpc. This was the theoretical background for GW experiments developed by the mid-1970s by Russian researchers.

At the same time, the first experimental efforts were performed by Braginsky's group at MSU jointly with the Institute of Physics of the Earth (IPE) of RAS (E I Popov's Department of Gravi-Inertial Detectors). The search for coincident signals on Weber-type antennas separated by 30 km was repeated [30]. Parameters of solid (duralumin) resonant detectors were close to Weber's; however, the registration system was different. The idea of a parametric transducer (sensor) with external pumping was realized. For this, the acoustic resonators (bars) were specifically shaped with horizontal consoles on the cylinder surface (Fig. 1). Between the consoles were mounted capacity sensor plates included in a radiophysical oscillation contour. The small working gap ($\approx 0.1$ cm) was kept by a guiding system with a thermal driver (controlled heating), i.e., an antenna with active maintenance of the 'operation point' (which was a prototype of modern GW interferometers with multiple feedback loops). In addition to an enhanced electromechanical transformation coefficient (due to the amplitude pumping of the contour), this construction had enhanced shielding from cosmic rays (direct action of a charge particle flux on the sensor), in contrast to Weber's installation, in which piezoelectric crystal coating of the bar was used. Later, this 'Russian antenna' was named 'Snail' because of the presence of consoles ('tentacles').

Observations with a pair of such detectors for several months did not discover any significant coincident signals on the detectors with the amplitude $\sim 10^{-16}$ [30–32], in contrast

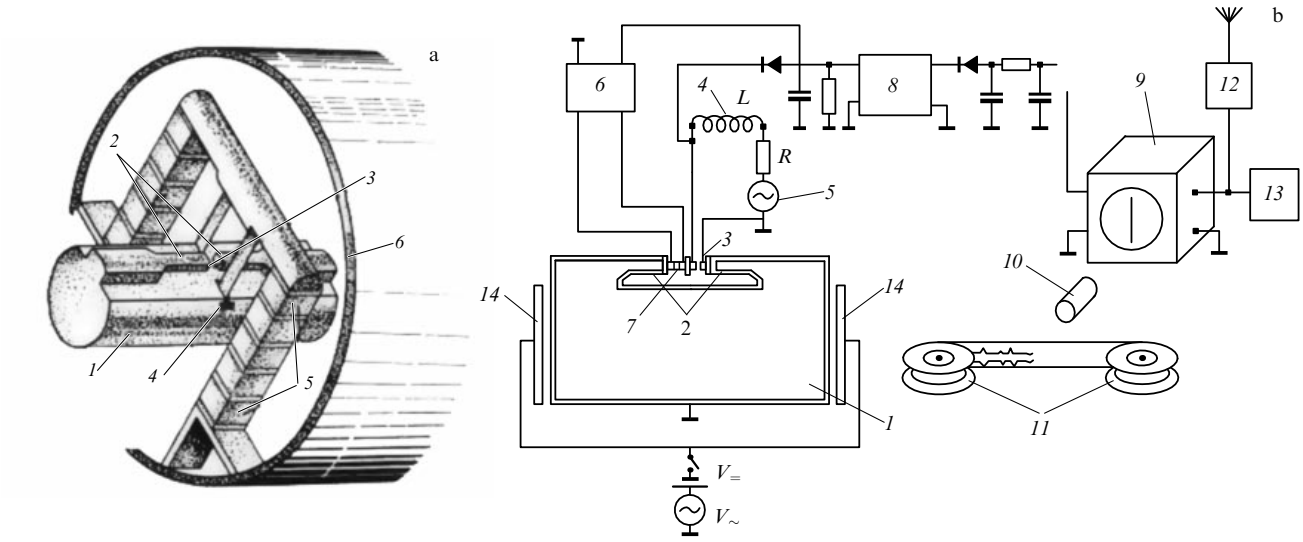


**Figure 1.** (a) General view of a gravitational bar detector: *1* — detecting aluminum cylinder, *2* — console rods ('tentacles'), *3* — point of attachment of the measuring capacity of a displacement sensor, *4* — dovetail fixation of tapes, *5* — antiseismic filter, *6* — vacuum camera. (b) Schematic of the measuring system: *1* — aluminum cylinder, *2* — 'tentacles', *3* — measuring capacity, *4* — inductivity of the capacity sensor contour, *5* — quartz pumping generator, *6* — guiding system, *7* — control element of the guiding system (electric furnace), *8* — narrow-band amplifier, *9* — tow-beam oscillograph, *10* — objective, *11* — drive mechanism, *12* — precision time signal receiver, *13* — quantum generator of time marks (quartz clock), *15* — calibration system.

to Weber's experiments, which reported up to five detections per month [20]. The absence of significant responses corresponded to theoretical expectations [21, 22] of the reasonable GW signal amplitude at the level $h \sim 10^{-18}$. All stronger signals were either technogenic or, in the best case, of geophysical origin. Similar results were obtained in the USA [33, 34], Italy [35], and England [36]; the final review is given in [37]. Thus, in the mid-1970s, the problem of increasing the sensitivity of GW detectors to metric variations by at least two to three orders of magnitude became very relevant.

Because the sensitivity of solid GW antennas is fundamentally limited by thermal (Brownian) noise of the acoustic resonator, the deep cooling of the resonator (to liquid helium temperatures and below) is needed. Two ways to achieve this goal were proposed. The first method was the direct solution to the problem by constructing large cryostats enabling the cooling of massive metal bars (with a mass of 2–5 t) to temperatures below 1 K [38, 39]. There was no such a laboratory technique at that time. It had to be developed using the principle of solution refrigerator dissolving of $He^3$ in $He^4$, which was quite an expensive task. Here, Italian groups [40] that constructed two detectors in Italy and one at CERN [41] were the most successful.

The second, more original and less expensive method proposed by a Russian group [42] was based on the use of dielectric bars with moderate mass but an enhanced acoustic quality factor. The formula for the limit sensitivity [42] constrained only by the Brownian oscillations of the resonance detector suggests that the minimal value of metric variations is proportional to a combination of the detector parameters, $h_{\min} \sim (T/MQ)^{1/2}$. The same value of this factor can be achieved by cooling large masses $M \sim (2-5) \times 10^6$ g to $T \sim 1$ K, with a moderate quality factor $Q \sim 10^6$, or significantly lower masses $M \sim 10^4$ g, but with a high quality factor $Q \sim 10^8 - 10^9$. Such quality factors for longitudinal mode oscillations can be achieved in ruby and sapphire cylindrical samples, which are especially grown for laser resonators.

In joint MSU–IC (Institute of Crystallography, RAS) experiments, record quality factors of $5 \times 10^9$ were achieved [43, 44]. The manufacturing and exploitation of a cryostat for purely laboratory masses $\sim 10^4$ g was not an unsolvable problem. To turn the sample into a GW detector, it had to be shaped and profiled to shift its resonance frequency into the range of $\sim 1$ kHz.

Unfortunately, this research project was not supported later, partially due to funding shortages at the Academy of Sciences at the end of the 1980s, but mainly due to the focusing of GW antennas on large-scale laser interferometers. In contrast, the European program of cryogenic bar detectors was fully completed: its history is reviewed in a recent paper by Pizzella [41]. We note that cryogenic bar GW antennas used DC SQUID (Superconducting Quantum Interference Device) sensors as modern types of parametric sensors with self-pumping at an UHF Josephson frequency $\sim 10^{10}$ Hz [38]; this shows that Braginsky's ideas about the effective conversion of GW perturbations into an electromagnetic signal [19] were fully realized. The theory of application of quantum magnetometers (SQUIDs) in cryogenic GW bar detectors was also presented in Russian papers [45, 46].

## 4. Detection of low-frequency gravitational wave signals

Weber's idea to use Earth as a resonant detector [10, 11] in quadrupole modes was also developed further. The paper by Bough and Kuhn [47] should be mentioned, in which the authors used seismic and gravimetric observations of Earth quadrupole noise modes to derive an improved estimate for the spectral density of the GW background in the frequency range $10^{-3} - 10^{-4}$ Hz. These estimates in the best case were at the level of $10^6 - 10^8$ erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$, i.e., somewhat below the Weber estimate.

The Russian scientific school put forward an alternative program of seismographic detection of gravitational radia-

tion bursts at higher frequencies (0.01–1.0 Hz) [48]. This was partially stimulated by F Dyson's paper discussing the possibility of GW detection from pulsars using ground-based seismographs in the case of favorable local rheology. Also intriguing were reports (later not confirmed) on experimental seismic registration of signals at pulsar frequencies by foreign [50] and Russian [51] groups.

The decisive motivation, however, was the theory of block structure of the terrestrial crust developed by the school of M A Sadovskii at the IPE RAS [52]. According to this theory, the tectonic subground of the terrestrial crust is not monolithic and is split into individual blocks (enhanced density zones) with the characteristic size of 50–100 km. For the speed of sound of $\sim 3$ km s$^{-1}$, such a block can be considered a resonant gravitational detector at a frequency of $\sim 0.01$ Hz and the quality factor $\sim 500$. A sensitive seismograph can serve as a sensor for this detector. It is also remarkable that exactly at these frequencies there is a gap in the seismic noise spectral density (a decrease by more than an order of magnitude on the Peterson curve [53]). In addition, the astrophysical prognosis of the expected GW bursts in the frequency range 0.1–0.01 Hz is more favorable for bursts with amplitudes $h \sim 10^{-16} - 10^{-17}$ [54].

This program was pursued in [55]. Optimal filtering algorithms of signals from a seismic antenna network elaborated earlier in [56] were used. The basic data were taken from six seismographs from the Terrascope array in southern California (there was no Russian digitized data at that time). The Earth model required for the analysis was taken according to [57] but with a translation (limit transition) to higher frequencies from mode frequencies. To filter the correlated noises, the coordinates of each individual seismograph were taken into account. No significant metric variations at the level of $h \sim 10^{-14}$ were discovered. This experimental estimate corresponds to the seismic displacement amplitude $\sim 10^{-8}$ cm and the GW energy flux $\sim 10^{8}$ erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$. The experimental limit turned out to be two orders of magnitude higher than the optimistic astrophysical expectation $h \sim 10^{-16}$, but was one order of magnitude better than the previous Dyson limit [49]. Clearly, further progress in solving this problem can be related to the use of a global seismograph network and longer observational times.

The data from seismographs in Moscow and Obninsk were also involved here but for a different reason: to search for anomalous seismic perturbations during the supernova explosion SN 1987A. The driving motivation was the sensational detection of correlated neutrino signals by four underground neutrino telescopes simultaneously: IMB (Irvine–Michigan–Brookhaven) (USA), Kamiokande (Japan), Mont Blanc Laboratory (Italy), and BNO INR RAS, which coincided in time with the supernova explosion SN 1987 A in the Large Magellanic Cloud ($\sim 52$ kpc) [58]. Also reported was the detection of 'coincident bursts' of gravitational radiation by resonant room-temperature bar detectors in Rome and Maryland [59]. Thus, a rare galactic event, a relativistic cosmic catastrophe, was simultaneously detected in the optical, neutrino, and, it seemed, gravitational channels. Presently, only correlated neutrino bursts are confirmed, i.e., core-collapse neutrinos have been registered. A thorough a posteriori analysis of the 'coincidences' in the data from GW detectors put the reality of the detection into doubt [60, 61].

When critically analyzing this event, different control tests were used, including a test of the presence of reactions of seismic sensors correlated with signals from resonant GW bar detectors. This study was carried out by a group from the Sternberg Astronomical Institute of MSU (SAI MSU) jointly with the IPE RAS [62]. Data from seismic observatories in Obninsk and in Moscow were used. A significant correlation with sensors in Obninsk was found, but there was no correlation with data from the Moscow station, which made it impossible to uniquely interpret the effect. Additionally, the orientation of the joint diagram of two detectors in Rome and Maryland was checked to be directed toward the Magellanic Clouds at the moment of suspicious 'gravitational coincidences'. Although the analysis in [63] gave a positive result (the detectors were directed toward the Magellanic Clouds), this did not remove other serious contradictions. Nevertheless, the case with SN 1987A has been very useful as the first example of a multichannel registration of a relativistic astrophysical catastrophe and pointed to the need to develop algorithms of joint data analysis from different instruments, thus opening the way to so-called multi-messenger astronomy.

As noted above, the seismic detection of GWs was appealing because it used 'natural antennas' at low frequencies, where astrophysical expectations gave increased GW burst intensities. This motivated the search for ways to decrease the resonance frequencies of bar detectors by changing their configuration, pass from longitudinal to transverse modes, modify their shape, etc. In this way, 'frame' and 'disk' bar detectors were built with eigenfrequencies at 100 Hz. Japanese groups were the most successful in this regard. In attempts to widen the detector diagram to cover a larger sky area for potential GW sources, an all-sky resonant spherical detector was designed. A description and analysis of such detectors and references to the original papers can be found in monograph [64].

Among the Russian projects, it is interesting to note the variant of a pendulum version of a resonance quadrupole detector on high-quality quartz (monolithic) pendulum suspensions to search for GW signals from pulsars at frequencies $\sim 1$ Hz, first proposed in [65] and later elaborated in detail in [66]. A general view of this detector is presented in Fig. 2. In a monolithic quartz block, end pendulums are formed on band suspensions with the eigenfrequency tuned to a specific pulsar, with a parametric capacity sensor of oscillations mounted in the gaps between pendulum masses $m$ and the block. General seismic perturbations are compensated in this construction. Thermal noises are suppressed owing to the high quality factor of quartz (tens of millions). The calculated sensitivity could be as high as $h \sim 10^{-20}$ with the linear block size (base) $l = 10$ m.

This project was not implemented, however. In spite of the use of low-frequency pendulum suspensions, it belongs to the category of resonant narrow-band detectors. The transition to a wide-band detector would be possible at the expense of operation outside the resonance frequency and compensation for the decrease in the transformation coefficient due to a significant increase in the detector base. A fundamental change in the oscillation registration scheme was required, which could not be accepted by the authors of the project at that time.

In fact, such a transition was realized in the first proposals [12] and prototype models of laser interferometric GW detectors [67] (registration using optical interferometry). If truth be told, it should be noted that the idea of 'free test masses' was not proposed in this work; it appeared later in a

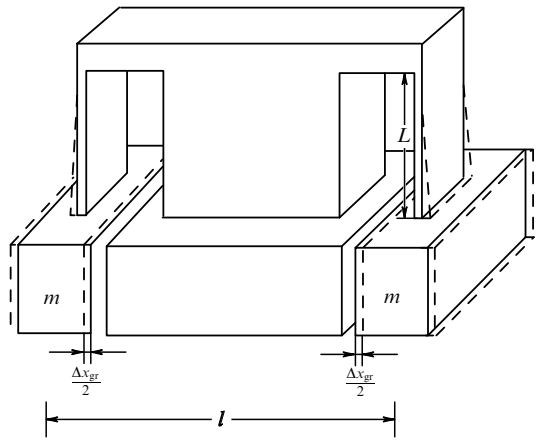


**Figure 2.** Low-frequency gravitational detector for GW radiation from pulsars ($\sim$ 1 Hz) with two high-quality resonance pendulums [65].

paper by Weiss [68] together with the idea of multiple reflections $N$ between mirror masses of the interferometer for the effective increase in the optical length: $L_{\text{eff}} = NL_0$. Clearly, the long base offers the possibility of measuring smaller deformations with the same value of measured absolute displacements, i.e., $h = \Delta L/L_{\text{eff}} \to 0$ as $L_{\text{eff}} \to \infty$. However, the effective base is still limited and cannot exceed half the gravitational wavelength without losing the very effect of 'cumulative response' or violating the 'slow motion' approximation for mirrors. At frequencies much higher than the pendulum frequency of mirror masses, 0.1–1.0 Hz, the mirror can be considered a free mass, which provides a wide-band range for the detector. For short perturbations (bursts) containing only a few periods of the carrier frequency, the loss of the possibility of 'resonant' amplification of the response is insignificant. The method of registration of the detector response by coherent laser interferometry has many characteristics exceeding those of other measurement methods used in radiophysical detectors, including cryogenic ones.

These features of the 'free-mass antenna' clearly stressed its advantage over solid-bar detectors, and only one — the need to precisely keep the operation point in the middle of the interference fringe — was the restraining factor that made the prospects for a reliable realization of such a device unclear. However, the successful demonstration of a 40 m prototype interferometer at Caltech [69] in the early 1980s removed the main obstacles, and the large-scale LIGO project was supported in the early 2000s. As mentioned in the Introduction, groups from the MSU Faculty of Physics and IAF RAS joined this project.

At the same time, the SAI MSU group jointly with BNO INR RAS bolstered work at BNO. A 100 m laser deformograph for geophysical research was built and put into operation in the main tunnel [70, 71] as a prototype for a GW interferometer (at the initial stages, a group from the Vavilov State Optical Institute also participated in this project [72]). Then, an intermediate LINGRAN-100 (Laser INterferomter of Gravitational waves of the Academy of Sciences) project [73, 74] was developed. The project assumed the construction of a laser GW interferometer of a combined type (Michelson–Fabry–Perot) with a sensitivity $h \sim 10^{-21}$ in the frequency band 100–1000 Hz in the existing tunnels of BNO. Unfortunately, the financial situation at the end of the 1990s did not allow this project to be carried out.

In these conditions, the SAI MSU group, having working contacts with the Japanese TAMA-300 project (National Astronomical Observatory of Japan) and Virgo (INFN, Italy, and CNRS, France), addressed the problem of registration by GW interferometers of low-frequency signals of both astrophysical and geophysical origin. An original proposal was formulated to use an interferometer with suspended mirrors as an angular gradientometer of the ground-level gravitational field [75]. The idea was to perform high-precision measurements of variations in the relative angle between two local vertical lines (mirror suspensions) separated by a long distance (3–4 km). If the light source (laser) is also suspended (injection bench), then such a system reacts only to the gravitational perturbations (variations in the gravity force) and filters out deformations (longitudinal and tilted). Such a possibility was studied in more detail in [76, 77] in the specific case of the Virgo interferometer, which has favorable suspensions (reduced to a 'one-string' configuration), which enables realization of the ambitious program of measurements of oscillations of Earth's core (as a by-product of the GW interferometer output). The direct high-precision measurement of tidal deformations by the Virgo detector was carried out by the SAI MSU group jointly with INFN (Pisa department) using the 'error signal' in feedback circuits maintaining the operating regime of the instrument [78].

The possibility of detecting low-frequency gravitational signals with the LIGO interferometers was also investigated. Experimentally, it was discovered that the 'imprint' of slow tidal deformations is present on the main 'signal' output of the interferometer (the differential output of destructive interference) in the form of modulation of the harmonics in the intermodal frequency interval of the Fabry–Perot (FP) interferometer arms [79]. As the arms' length was kept constant with high precision by feedback loops, the result seemed intriguing: it appeared that the relativistic effect of gravitational shift of the electromagnetic (EM) beam (equivalent to a change in the refractive index along the arms due to gravitational perturbations) could be measured [80]. However, a more careful study carried out by the SAI MSU group showed that the reason was the residual deformation of the arms, which is below the accuracy $10^{-12}$ m of their maintenance [81]. Nevertheless, the possibility of using a channel in the intermodal frequency interval (the photon circulation frequency in the FP arms) for registration of low-frequency GWs and weak geophysical perturbations remains topical [82].

## 5. High-frequency radiation

As mentioned above, the frequency range of laser GW interferometers is limited from above, $\omega \leqslant \omega_{\max}$, by the signal accumulation and 'slow motion' conditions. However, there is a special regime in which coherent detection is possible for frequencies exceeding $\omega_{\max} \sim 10^5$ rad s$^{-1}$. Such a possibility was first considered in the original paper by Grishchuk [83], who studied the acceleration of test particles (balls) between two elastically reflecting surfaces in the field of an incident gravitational wave. It was shown that under the special resonance condition, when the GW frequency is equal to the frequency of circular motion of the balls between the surfaces, a monotonic acceleration of the balls occurs due to the GW energy.

In [84], this idea was applied to photons in an optical FP cavity. The dependence of the effect on the incident angle of

GWs to the interferometer was noted, which in principle enables the determination of the GW incidence direction. Finally, a GW interferometer in full configuration under this 'gravitational–optical' resonance condition was analyzed in [85], where the spectral bands of high-frequency detection were calculated. Tests of this regime on the LIGO and Virgo detectors have not been carried out so far, mainly due to the nontrivial problem of the existence of astrophysical sources of such high-frequency GWs. Some ideas can be found in [86]; however, no specific sources with known coordinates have been found yet.

Nevertheless, high-frequency gravitational radiation has been studied quite actively in connection with the analysis of the possibility of realizing the laboratory Hertz experiment for GWs.

Weber [10, 11] considered an experimental setup including a generator and a GW detector based on forced resonance acoustic oscillations of a cylindrical solid piezo-electric bar with sizes $l \sim d \sim (0.5-1)$ m and the characteristic frequency $\sim 10^4$ Hz. He found that for the oscillation amplitude at the destruction threshold of the sample, the generated GW power reaches $10^{-13}$ erg s$^{-1}$, which is much smaller than the possible detector sensitivity, which can reach $\sim 10^{-3}$ erg s$^{-1}$.

Russian scientists revisited Weber's calculations many times and attempted to actually carry out experiments. For example, in [42], a mechanical (acoustic) variant of the gravitational generator was considered in the form of a coherent set of emitters at a frequency of $\sim 10^7$ Hz with the expected GW power being an order of magnitude higher: $\sim 10^{-11}$ erg s$^{-1}$. However, it turned out to be impossible to adjust this power to the sensitivity of the resonance acoustic bar detector, even with extreme parameter values (quality factor $10^{14}$, temperature $10^{-2}$ K). The idea that this could be done using EM UHF resonators [87] had little success.

In the 1970s, experimental studies of a GW Hertz experiment were carried out at the Institute of Radioengineering and Electronics (IRE) of the USSR Academy of Sciences (presently, Kotel'nikov IRE RAS) (M G Golubtsov's group) using magnetostriction materials [88]. An original approach was proposed. The understanding of the contradiction between the high driving frequency and the acoustic resonance condition (which had to be maintained in order to maximize the amplitude) led to a compromise solution, the so-called parametric stretching of the acoustic wavelength. The frequency transformation in the EM cavity with a nonlinear element, a magnetostriction sample (generator), applied a driving force to the sample that excited high-frequency induced oscillations (homogeneously in the bulk) with the form coincident with the principal transverse mode. The simple driving by a high-frequency force would excite a high-order mode, with the adjacent half-wavelength pieces making mutually compensating contributions to the GW emission and therefore only end regions with much smaller masses being efficient (which was already noted by Weber [10]). Thus, in a magnetostriction medium, a parametric transformation of the energy of low-frequency acoustic modes into high frequencies would occur.

To detect GW emission, the following inverse variant of a graviacoustomagnetic transducer was proposed. A prototype model was manufactured at a frequency of $\approx 100$ MHz (sample of the volume 1 m$^3$ and mass $\approx 10$ kg) (the variant at $T = 4.5$ K was considered), which was studied until the mid-1980s. Then the research was stopped due to the resignation of the leaders.

At the Joint Institute for Nuclear Research (JINR) (Dubna), an approach was developed based on the interaction of traveling waves (optical, acoustic, and gravitational) in a nonlinear medium [89, 90]. To keep the resonance and driving amplitude at high frequencies, the size and mass of the relevant elementary quadrupoles had to be decreased by passing, in principle, to the molecular level. The mass deficit is then compensated by a large number of coherent emitters, up to $10^{22}-10^{24}$ per cm$^3$. The molecules of the medium with a large quadrupole moment should be used. The medium should be highly nonlinear (optopiezoactive) to ensure the interaction of the optical, acoustic, and gravitational waves in the process of their propagation under the condition of the corresponding wave synchronism. In [91], Pisarev and Bogolyubov proposed matrix crystals to be used as the medium: these artificial materials include molecular hydrogen dissolved in argon, which solidifies at the liquid helium temperature. The expected GW power is 1 erg s$^{-1}$ for the optical pumping power up to 1 GW in the economy pulse mode. The studies started and continued until the crisis of 2000.

In fact, the proposed principle and experimental method ideologically correspond to papers by Gertsenstein [13] and Zel'dovich [14] cited in the Introduction but transferred from natural to artificial laboratory conditions. The same type of GW Hertz experiments was suggested in the project by Kopvillem and Nagibarov [92], who proposed using the interaction of powerful laser beams in optical nonlinear media.

One more qualitatively new idea related to laboratory GW emission was put forward by V A Belokon', who proposed pulsed GW generation by laser mini-explosions [93]. Because the generated power $P_g$ is proportional to the sixth power of the resonance acoustic oscillation frequency or the velocity of sound in the emitter material, media with a high speed of sound should be used or made artificially, for example, by explosive compression of the target. During adiabatic compression, the speed of sound $v_s$ increases as $v_s \propto \rho^{1/3}$ and the radiated power as $P_g \propto \rho^2 v_s^6 = \rho^4$. These proposals consider GW emission from the target in the form of an aluminum foil pie (book) squeezed by oppositely directed laser beams. At high power, the giant light pressure compresses the plates to transform them into plasma in which multiple reflecting shocks generate a GW pulse. The calculations give the following result. For the laser power $P \sim 1$ W, the sound velocity reaches $10^8$ cm s$^{-1}$ and the pressure is $10^{10}-10^{11}$ atm. The power of the emitted GW pulse is $P_g \sim 1$ W with a duration of $10^{-10}-10^{-11}$ s. Recognizing the originality of this proposal, it remains unclear how this GW pulse can be detected. No such experiments have been carried out so far.

To complete this section, we present the results of an analysis, performed recently in [94], of a gravitational Hertz experiment in the optical frequency range based on the Gertsenstein–Zel'dovich effect. This analysis can be of additional interest in view of the proposals to use such detectors to register the primordial GW background at optical frequencies [95].

The laboratory GW emitter is considered in accordance with the direct Gertsenstein effect: an intensive EM pumping (laser beam) passes through a region with a strong magnetic field in which a coherent GW is generated and propagates in parallel with the EM wave. At the next stage, the emerged GW passes through a strongly magnetized zone (the laser

beam is deflected away). According to the inverse Gertsenstein–Zel'dovich effect, a weak secondary coherent EM wave arises in this zone, which can be photodetected. Such systems have been considered earlier but with negative results: for reasonable parameters of the pumping intensity and the magnetic field, realistic geometry (size of the installation), and photodetector noises, it was impossible to adjust the emitted GW power with the detector sensitivity.

To overcome this difficulty, a fundamental modification to this scheme was proposed. A high-quality optical FP cavity was mounted in the magnetic field zone of both the emitter and the detector. The purpose was to increase the optical path in the interaction region of the pumping wave (in the first zone) and the signal wave (in the second zone) with the magnetic field, because the generation effect is proportional to the interaction length. This step requires special justification because direct and inverse conversion effects were initially formulated for free space. At the qualitative level, such a justification was provided in [94]; however, rigorous analytic arguments have yet to be elaborated.

Another fundamental technical detail is the use in the detector of an FP resonator with a modulated quality factor, which sharply turns off (decreases) after the end of observation (measurement). The accumulated 'signal' EM energy in the form of a short pulse arrives at the photodetector.

Only the possible detector sensitivity on the quantum noise background due to vacuum emission was estimated in [94]; technological characteristics are still to be investigated. Nevertheless, on the theoretical level, it is possible to adjust the GW emitter and receiver for the following fiducial parameters of calculations: the physical length (tube) of the interaction region $L = 100$ m, the magnetic field strength $H = 10^5$ G (10 T), the EM wavelength 1 μm, and the FP resonator finesse $F = 10^8 - 10^9$. With such very extreme parameters, the 'adjustment' of the Hertz experiment occurs at an extremely small GW amplitude, $h \sim 10^{-31}$, for the accumulation time of the order of a few days. This corresponds to the primordial GW background at optical frequencies, produced by parametric amplification of gravitons in the metric of the expanding Universe [96].

## 6. Optoacoustic gravitational antenna

Difficulties with fundamental research in Russia at the end of the 20th – beginning of the 21st centuries, in addition to other factors, were related to continued shortages of funding. This was especially harmful for experimental activity. A scientific group in any country, in proposing a project, should of course take real economic conditions into account. But in Russia this factor became decisive, while the conditions that the experiments be advantageous, fundamental, and at the world level were still imposed. In other words, one had to do something "very serious but for very modest money." The LINGRAN project mentioned in Section 4 did not comply with these conditions (although it was quite cheap in world prices: 5 mln USD over five years). As a result, by the time of the discovery of gravitational waves, we did not even have our own 100 m prototype of a large-scale interferometer. Against this background, the building of the optoacoustic OGRAN installation in the underground tunnel of BNO INR RAS should be considered as a moderate but evident success.

The idea of a gravitational antenna as a combination of principles of resonance bar detectors and laser interferometers with free masses was discussed in the middle of the 1980s. It was almost finally formulated in [97] in discussing a Weber detector with an optical FP resonator attached to its surface and fed by an external stabilized laser. The scale of both degrees of freedom, acoustic and optical, was assumed to be the same (mirrors of the FP cavity fixed at the flat ends of a cylinder detector); therefore, when calculating the detector reaction to a GW, the multiplicative character of the interaction should be taken into account. For detectors with an optical sensor in the form of an FP resonator with a micrometer gap, as in [98], this was not required, because the sensor detected only acoustic oscillations. As a result, in the combined detector, a complex response emerged that contained both optical and acoustic components, which, in principle, should have facilitated the filtering of noise. Another important feature of such a configuration was the smallness of the fluctuation back reaction of the optical degree of freedom on the acoustic one [17]. This effect appeared through fluctuations of the light pressure on the interferometer mirrors, which becomes critical only for a very high pumping power (more than 10 kW). For an intermediate pumping power of the order of a few watts, this effect is insignificant, and it is possible to increase the transformation coefficient of the signal by increasing the pumping power. Here, the photon noise level decreases as the square root of time. As a result, the optical (interferometric) detection system is presently the most precise. This is proven in practice by the LIGO and Virgo detectors, in which record small absolute displacements of the mirrors, $10^{-16}$ cm, are measured.

In the combined antenna, the photon noise level can be so small that the main noise background is due to thermal Brownian oscillations of the acoustic detector (the sensor looks like an ideal detector). Here, the methods of noise suppression are well known: a high acoustic quality factor and cooling of the detector are needed. But even at room temperature and intermediate quality factors ($\sim 10^5$), the detector sensitivity to metric variations can reach $\sim 10^{-20}$ in the frequency band around a few hertz at the detector resonance frequency. Interestingly, this is comparable to the sensitivity of cryogenic bar detectors, but can be achieved without deep cooling.

The specific parameters of the optical and mechanical parts of the combined OGRAN antenna were calculated in [99]. It was found that to suppress the optical noise, a very high finesse of the FP resonator $F \geqslant 10^4$ is needed, i.e., high-reflectivity mirrors with tiny absorption (less than a few ppm) should be used. Later, such mirrors were manufactured for OGRAN by the Laboratoire des Materiaux Avances optical factory (Lyons, France).

The development of OGRAN as a joint project of MSU and the Russian Academy of Sciences (SAI MSU, INR RAS, and the Institute of Laser Physics (ILP) of the Siberian Division, RAS) started in 2005 with the ultimate goals of constructing an original GW antenna and installing it for long-term observations in the underground tunnel of BNO INR RAS. The project was financed by the Center for New Prospective Technology (CNPT) RAS. The construction of the device was mainly completed in 2012: the antenna was assembled, and its testing at SAI MSU showed characteristics close to the projected ones. In 2014, the antenna was moved to BNO, where the construction of a special underground laboratory 1500 m from the entrance to the main tunnel had been competed by that time. As of the time of writing, work

on the automatic maintenance of the operation regime and precision thermostabilization are being completed. A detailed description of the OGRAN antenna with technical characteristics can be found, e.g., in [100, 101]. Below, we briefly describe the structure of this antenna.

The antenna is built using the classical scheme known as the comparator of frequency etalons, in which the detected signal results from a comparison of a pair of high-stability optical cavities (Fig. 3). The external single-mode laser, which is used for the optical pumping of the antenna, is included in the feedback loop with a high-quality optical Fabry–Perot etalon. The mirrors of this etalon are fixed at the flat ends of the detector — a large aluminum cylinder (acoustic cavity) of length $L = 2$ m and mass $M = 2$ t with a central hollow channel for the optical beam.

A GW perturbs both the acoustic and optical degrees of freedom by shifting the optical resonance frequency. The feedback loop correspondingly rearranges the laser generation frequency by keeping the resonant tuning. Thus, gravitational perturbations are encoded in variations of the pumping frequency of the antenna. These variations are registered using a differential setup (comparator) containing a second short FP etalon ($l = 15$ cm) operating as the optical frequency discriminator. To increase temperature stability, the etalon body is made of a material with an ultra-low thermal expansion coefficient, sitall CO-115M [102].

The initial operation regime, or operation point of the antenna, exactly corresponds to the resonance tuning of both optical resonators. For the large (detector) cavity, this is achieved by changing the laser pumping frequency. One of the FP mirrors of the reference resonator (discriminator) is attached to piezo-ceramics, which at low frequency is controlled by the feedback loop tension. The resonance frequency of the discriminator is fixed at low values (less than 100 Hz). At signal frequencies close to 1 kHz, the discriminator mirrors are free, and the difference signal from the comparator is proportional to the GW perturbation frequency. The error signal in both arms (of the detector and the discriminator) is obtained using the well-known Pound–Drever–Hall scheme, which assumes the introduction of a phase modulation at the radio frequency of the input optical radiation (about 10 MHz) [103]. The beam reflected from the reference cavity (discriminator) is synchronously demodulated at the photodetector. The photocurrent amplitude is proportional to the difference between the laser emission and the eigenfrequency of the FP etalon of the discriminator, which is assumed to be sufficiently stable. Thus, the output signal depends only on perturbations of the resonance GW detector. For stable operation of the entire antenna, laser pumping amplitude stabilization is also ensured.

The optical system of OGRAN in the absence of external gravitational perturbations must operate in the regime of the zero output signal (operation in the 'dark spot', as adopted in all long-base laser gravitational interferometers). At the same time, it does not require the interference of two beams, which significantly facilitates the technical realization of the detector.

The program of observations of the ground-level gravigradient background by OGRAN envisages its joint operation with the BNO underground scintillation neutrino telescope. The search for neutrino–gravitational events — time-coincident excitations of both detectors — can substitute the traditional coincidence scheme of identical but spatially separated detectors. This corresponds to the idea of multichannel observations of relativistic astrophysical catastrophes [104].

The underground location of OGRAN drastically decreases the flux of high-energy cosmic particles that can produce nongravitational triggers in the antenna. This made it unnecessary to perform parallel control and anti-coincidence filtering of radiation from the cosmic background by special sensors, as in the case of ground-based cryogenic antennas [41]. However, to filter out gravitational perturbations of geophysical origin, a Weber-type detector (Snail) is installed near OGRAN, which was previously used to test Weber's experiments in the 1970s and was revived in the 1990s at SAI MSU [105]. Its sensitivity is insufficient for detecting cosmic GW pulses. Anti-coincidences with its output data can

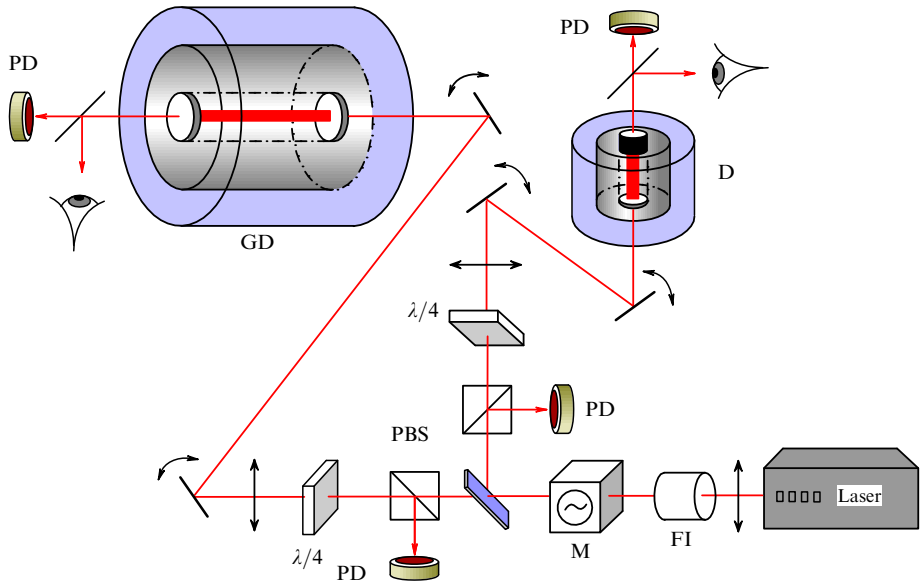


**Figure 3.** Principal optoelectronic scheme of the OGRAN detector. GD — gravitational detector, PD — photodetector, D — discriminator, FI — Faraday filter, M — modulator, PBS — polarization beam splitter.

be used to significantly decrease the suspicious noise bursts in OGRAN [106]. Interestingly, the Snail data were also used as a filter of geophysical signals to test the effect of excessive coincidences in the galactic disk plane measured by the cryogenic detectors Explorer and Nautilus [107].

Further development of the OGRAN detector within the available funding is associated with an upgrade with the aim to cool its acoustic detector to the liquid nitrogen temperature (about 77 K). The intensity of the Brownian noise of the detector should then decrease by four times due to the temperature lowering and by more than an order of magnitude due to an increase in the acoustic quality factor (up to 3–6 mln, as suggested by the cryogenic resonance bar detector experience). As a result, a sensitivity of about $3 \times 10^{-21}$ $\mathrm{Hz}^{-1/2}$ in the frequency band of 10 Hz is expected, i.e., OGRAN will 'reach to' the Virgo galaxy cluster. The key technological problem of the 'cryogenic' OGRAN is, of course, the problem of cryogenic mirrors, i.e., the possibility of preserving the efficiency of FP cavities at low temperatures [a similar problem is being solved in the Japanese project KAGRA (Kamioka Gravitational Wave Detector)].

Thus far, test experiments with the pilot model of the cryo-OGRAN with mirrors with a fluorite calcium base have been carried out [108], confirming the feasibility of this approach.

## 7. Conclusion

The presented review of work by Russian groups in the field of GW experiments (in the period of its appearance and initial development) demonstrates that despite the clear understanding of the significance of the problem, this area of research did not have sufficient support in Russia, comparable (even partially) to the funding of groups carrying out such studies in Europe and the USA. Nevertheless, under these conditions, much research significant for global science has been done. First of all, this is the elaboration of principal theoretical and experimental problems related to astrophysical sources of GWs, radiophysical aspects of the theory of GW detectors, and the optimization of data analysis in GW experiments. Studies of geophysical detection of low-frequency GWs, the development of GW Hertz experiments, and the building of the combined optoacoustic gravitational antenna are also original.

At the same time, the Russian groups that joined LIGO significantly contributed to the elaboration of physical grounds of future generations of GW interferometers. In particular, important studies were carried out on thermal restrictions in optical elements and units of the interferometer at high optical pumping power [6], as well as on the problem of excessive noise and the stability of operation regimes of such interferometers [5].

Very significant are Russian proposals on the substitution of the reflecting coating of mirrors by a diffraction one (structures with periodic variation of the dielectric permittivity), which is crucial for decreasing losses at high optical powers [109]. The development of the theory and methods of quantum nondemolition measurements in GW experiments [110] are especially important.

We recall that general quantum mechanical constraints on sensitivity in precision measurements with test bodies were first considered by Braginsky in his early paper [19]; a modern presentation can be found in [111, 112]. For a long time, this problem remained purely theoretical and was investigated on the level of thought experiments. However, the successes of LIGO, Virgo, and GEO-600 in building detectors capable of measuring displacements of mass mirrors as small as $\sim 10^{-16}$ cm made this problem relevant in practice. It is now unclear which of the principal schemes to surpass quantum mechanical constraints proposed in [110] will be realized in third-generation antennas, but the leading role of the Russian school in this field is indisputable already today.

Of course, the astrophysical aspect of GW experiments remains of fundamental importance, which in fact motivated all other studies on the development of the GW detection technique. Presently, a noticeable number of significant papers are being published in Russian journals. Here, the method of detection of ultra-long-wavelength GWs, with periods of $\sim 10^7 - 10^8$ s, by the pulsar timing should be mentioned. The idea itself was first discussed by Sazhin [113] and independently by Detweiler [114]. A detailed development of this method has been performed by Australian radio astronomers from the Parkes Observatory [the project PPTA (Parkes Pulsar Timing Array)] to detect a stochastic GW background in the Universe [115]. In our paper [116], irregular moments of arrival of pulsar pulses were studied to discover GWs from supermassive binary systems. These studies continue (jointly with the PPTA collaboration) with the aim of increasing the sensitivity by using the group timing (the mean estimate of the GW background intensity using data from a group of independent pulsars) [115].

The enthusiasm of astrophysicists and theoreticians and relativists after the first announcement of GW detection from coalescing binary black holes (BHs) is related to the hopes to construct a new instrument to study the properties of space–time under extreme conditions. Indeed, GW detection itself means two fundamental discoveries simultaneously: (1) proof of the reality of GWs predicted by GR, and (2) decisive proof of the existence of BHs among the stellar population of the Universe [117] (another GR prediction). While earlier BH candidates were discovered by their X-ray accretion emission, and parameters have been estimated from the dynamics of their companions in binary systems, it is now possible to directly observe the final stage of the evolution of binary systems.

To a large extent, the fundamentals (in the physical sense) of such observations have been elaborated by Russian astrophysicists since the end of the 1960s.

In particular, papers by Novikov, Frolov, and Cherepashchuk [118–120] pointed out which specific information on the nature of the object can be extracted from GW observations. We list only a few possibilities. During the coalescence of a black-hole–neutron-star (BH–NS) binary system, the structure of the GW signal enables an estimation of the NS equation of state. The form of the GW signal at the final ring-down stage enables observations of the oscillation modes of the BH carrying information on the event horizon, i.e., information on the presence or absence of the event horizon (its physical state), studies of 'naked' singularities, and testing the no-hair theorem for BHs (in other words, the dynamics of empty space–time). Using GW signals from coalescences of supermassive BHs (in galactic collisions), it is possible in principle to observe ultra-long-wavelength GWs generated in the early Universe [121]. Such GWs were generated when the primordial inflationary (de Sitter) stage was superseded by Friedmann expansion, when the age of the Universe was as small as $10^{-36}$ s (the wavelength of such GWs is more than 1 Mpc) [122], etc. Last, GW signals can be a decisive tool to search for exotic objects such as wormholes [116].

In recent years, the strategy of searches for GWs from cosmic objects has been dominated by multi-messenger astronomy, which we already mentioned in Section 4. This in fact manifests the tendency to realize multi-channel observations of sporadically appearing cosmic catastrophes [123]. A similar method was already used by the SAI MSU group much earlier (in terms of ''searches for astro–gravity correlations'' [124]). The analysis of data from the Italian gravitational wave antennas was carried out jointly with data from underground neutrino telescopes and gamma-ray burst detectors from BATSE (Burst and Transient Source Experiment) [125–127]. The main motivation was to reduce the bulk of data from GW detectors to be processed: the data were taken only from time intervals in the vicinity of detected gamma and neutrino bursts. Presently, the inverse 'trigger approach' is predominantly used: the search for electromagnetic or other radiation counterparts that could arise immediately after GW candidate events (which is possible due to the zero rest-mass of the graviton). Here, SAI MSU has taken one of the leading positions in the world due to the construction of a global network of MASTER optical robotic telescopes by Lipunov's group [128].

In completing the history of GW experiments in Russian science, we try to speculate about their future development. The previous period can be conditionally called the period of first discoveries. Leading groups in different countries worked competing with each other for being the first discoverers of the new type of radiation. Because this has been related to very expensive devices, the groups with higher funding had an advantage, which ultimately led them to success.

Now that the first discovery has been made and the first discoverers are known, one can start routinely studying the new phenomena (a new type of matter) to extend our knowledge about the Universe. Such an understanding of the current situation means that Russian science faces the need to construct its own instrument, a large-scale gravitational interferometer, which, of course, will be included in the global network of GW detectors in the future. Monitoring quasistatic gravitational perturbations to solve fundamental problems of geophysics and geodynamics could be a solid byproduct of this detector.

The issue of a Russian GW observatory has been periodically discussed with foreign colleagues at different meetings and conferences, in particular, during the last ICGAC-12 (Twelfth International Conference on Gravitation, Astrophysics and Cosmology) on June 28–July 5, 2015 in Moscow at the People's Friendship University of Russia (RUDN) [129]. Calculations show that for the optimal sky coverage by a worldwide network of GW interferometers, a GW interferometer located in central Siberia would be the most favorable (e.g., in Akademgorodok near Novosibirsk). At the same time, for the underground location, the most advantageous place would be BNO INR RAS in the north Caucasus. Clearly, the choice of the site of the gravitational observatory requires additional analysis and discussions.

Undoubtedly, the corresponding long-term project must be multi-disciplinary, with the involvement of several RAS institutes, research and production associations (RPAs), and leading universities. These last can be the main 'drivers' of the project, which can form prospective teams of researchers for years. It is no secret that the 20-year period of disintegration of the RAS came at a high cost for Russian science: first of all, due to the loss of many young researchers without whom long-term projects cannot be realized. Nevertheless, the senior generation of 'relativistic' experimentalists is still active, and they can attract and educate new students.

As regards the technology and know-how, total decay, fortunately, has not occurred. For example, there are well-elaborated technologies, such as the manufacturing of powerful single-mode lasers stabilized by different methods, including the use of high-quality FP resonators (the Pound–Drever–Hall technique [101]) (Lebedev Physical Institute, RAS, and Institute of Laser Physics, SB RAS), the manufacturing of highly reflective mirrors with low losses (RPA Polus), the manufacturing of high-quality acoustic resonators and suspensions (Faculty of Physics of MSU, and Shubnikov Institute of Crystallography, RAS), etc. Of course, the experience of constructing the OGRAN antenna should be added. Its optoelectronic and optomechanical technologies in many aspects correspond to those used in the LIGO and Virgo detectors.

OGRAN can be used as a testing ground for elaborating units of new GW interferometers. The industrial components of the projects can also be manufactured. In Russia, there are factories and technologies to produce stainless vacuum tubes of large diameter, the technique of high-vacuum (oil-free) pumping of large volumes (RPA Gelijmash, RPA Vacuum Technique), not to mention the construction of underground tunnels. All these can be combined to solve fundamental scientific problems. Decisions by high authorities, effective management, and sufficient funding are all that is required.

While awaiting this unfortunately not very likely event, the existing research groups will continue their studies in GW astronomy in the framework of the actual possibilities, including support from the Russian Academy of Sciences and the Russian Foundation for Basic Research, as well as modest support from foreign colleagues.

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