Gravitational wave experiments and Baksan project
“OGRAN”

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Abstract

A brief sketch of the present status of gravitational wave experiments is given. Attention is concentrated to recent observations with the gravitational detector network. The project OGRAN for a combined optic-interferometrical and acoustical gravitation wave antenna planned for installation into underground facilities of the Baksan Neutrino Observatory is presented. We describe general principles of the apparatus, expected sensitivity and current characteristics of the antenna prototype; some ways for sensitivity improvement are also discussed.

\textbf{Keywords: gravitational waves, gravitational detectors.}

1 Introduction

Current status of the gravitational wave (GW) experiments is characterised by the well developed international net of gravitational wave antennae of two types: optical interferometers on suspended mass-mirrors and cryogenic acoustical resonant bars with the SQUID sensor. “Bar net” containing five independent detectors presented by IGCE \textsuperscript{1} and ROG \textsuperscript{2} collaborations is well developed and has a relatively long history of observation. “Interferometer family” composed by LIGO \textsuperscript{3}, VIRGO \textsuperscript{4}, GEO \textsuperscript{5} and TAMA \textsuperscript{6} recently started first individual and joint series of
observations on some intermediate sensitivity but a work for improving it is going on.

The modern cryogenic resonance bar detectors now are able to register metric perturbations at the level $10^{-21}$ in a narrow bandwidth on the order of few Hertz around the resonance frequency. Large base gravitational-wave interferometers currently can detect GW-bursts with the magnitude $\sim 10^{-19}$ and spectrum width of several hundred Hertz. It is believed that in a nearest future the free-mass interferometrical antennae will achieve the wideband sensitivity $10^{-22}$ which corresponds to the expected rate of events at least one per day and more. Approximately similar sensitivity might be reached by “big ball” detectors having the mass $30 \div 60$ ton cooled up to 10 mK [7] with advantage of the increasing expected rate of events due to the omni-directional antenna pattern. At present this type of detectors exists as a moderate scale prototypes [7] [8] [9] and a funding of the full scale projects is not solved completely. Thus one could say there is some “scientific competition” between solid body resonance acoustical detectors at one hand and wide band free-mass optical interferometers on the other hand. Despite of a visible potential advantage of the interferometers (excepting their cost which is ten times more the cost of bar detectors) both types in fact have a supplementary relation to each other taking into account the different mechanism of their interaction with gravitational radiation: a generation of acoustical waves for the bar and excitation of mass-mirror’s relative displacements for interferometers (in the last case the effect can be described also as variations of the optical wave length). This difference and also the observation some anomalous coincident events with bar detectors [10] [11] stimulated a discussion for a comparison of the cross sections both type of gravitational antennae which had been started after supernova SN 1987A event [12] [13] and renewed recently [14] after results published by ROG collaboration.

Meanwhile joint observations with bars and interferometers at the current level of sensitivity were carried out in past and its are continuing at present [15].

It was mentioned in many papers, see for example [16], that a sensitivity threshold in the GW searching is much higher the potential sensitivity of any individual detector due to the “blind character of all sky searching” when coordinates and parameters of a hypothetical source are unknown and one has to run over all conceivable positions and signal templates in a data processing. It increases a “chance probability” to get a false “noise event” or equivalently decreases the effective registering sensitivity. Although the declared aim of the present antenna net is an operation at the level of $10^{-21}$ the typical effective threshold of “bursts sensitivity” resulted in many recent observations is still occurred between $10^{-18}$ and $10^{-19}$ magnitude of metric perturbation. Such moderate sensitivity allows to overlap mainly sources located in a close environment of the Galaxy with the radius less then 1 Mpc i.e. this type of GW experiment can be called as a “search for rare events” with a hope to have a “lucky chance” of nearby “relativistic star catastrophe”.

In the papers [17] [18] it was proposed that the similar sensitivity might be achieved for a room temperature bar detector with an optical read out using an advanced optical technology (low noise optical frequency standards). Group of the cryogenic antenna AURIGA has developed a micro-gap optical transducer as a low noise alternative to the SQUID read out [19]. The authors of the paper [17] have analysed a more sophisticated variant of the optical read out with the optical FP-
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resonator extended along the bar body and in fact having the same scale as the bar itself. One can consider this construction as a combination of the bar and interferometer unified in the one detector and wait a more complex response under GW excitation containing the acoustical and optical parts independently in some extent. This idea now is in the process of realization in the form of Russian national project OGRAN (opto-acoustical gravitational antenna) \[20\].

In our report below we at first, review recent results collected by the existing net of GW antennae and at second, present more in details a current status of the OGRAN project.

2 Results of the GW searching

The principal filtration procedure in a searching for GW pulses (introduced by a pioneer of the gravitational wave experiment J. Weber \[21\]) consisted in a selection of coincident perturbations of widely spatially separated detectors. It is the straightforward method for an effective decreasing of the local noise background but more of that the coincidences (as it was believed) could guarantee in some extent a global (extraterrestrial) nature of registered signals. This procedure remains to be valid now but it is enriched (if not loaded) through a preliminary reduction of the detection noise by optimal filtering matched with a definite type of expected signal (see a short review in \[22\]).

The following “signal families” are considered more often: a) relativistic binary coalescence, b) supernova explosions (or more general,-collapses), c) pulsars, d) primordial stochastic GW background. However under a deficit of “a prior information” (no data of source’s position and parameters) the algorithm of matched filtering for such “blind search” becomes extremely cumbersome, requires a lot of computational time and power etc. It affects an ability of quick online detection and finally results in a decreasing of effective sensitivity. Nevertheless just in this manner a number of recent observations were performed. Results of some of them are presented below.

i) Interferometers.

LIGO collaboration has published a series of articles after the first short observational period called as “the first Science run, S1”; (23.08 - 09.09) 2002. Three interferometrical detectors were involved: two in the Hanford Observatory with the \(2 \, km\) base (H1) and \(4 \, km\) (H2) \[22\] and one \(3000 \, km\) apart in the Livingstone Observatory also with the \(4 \, km\) long base \[23\].

a) Result of the search for short GW bursts \[24\].

This program is more close to the original Weber’s algorithm of selection of very short coincident pulse-excitations at outputs of independent detectors. A typical new element introduced at present consists in a modelling of expected signals in two probable waveforms: a quasi \(\delta\)-pulse with Gaussian envelope, and similar pulse with a sine carrier,-the “sine-Gaussian” pulse. The carrier frequency and pulse time width (duration) were varied. So the “matched filtering” could be applied only as a multi-channel procedure. A preliminary noise filtering and selection of “GW-burst candidates” also was very sophisticated. It is reflected as a step by step reduction of the useful observational time interval \[24\]: 17 days (408 hours) (S1 time) - 96 hours
(effective duty cycle) - 35.5 hours (triple-coincidence time).

The final conclusion was in the determination of the “first upper limit from LIGO on GW bursts”. Roughly it was formulated as a statement that “with the confidential level 90% at the frequencies \((150 \div 3000)\) Hz short GW bursts with duration \((40 \div 100)\) ms and spectrum amplitudes \(h_f \sim (10^{-18} \div 10^{-19}) Hz^{-1/2}\) can be expected with the rate \(R \leq 1.6 day^{-1}\)”. The observation was performed in several frequency windows \(\Delta f \simeq 10^2 Hz\) inside the general bandwidth. Thus the threshold for admitted metric perturbations has to be defined as \(h \leq 10^{-17} \div 10^{-18}\). Below we shall compare it with bar’s observations.

b) Search for GW from binary neutron stars coalescence \[25\].

This program is known as a detection of “chirp signals”, i.e. short GW pulses with sweeping carrier which have to be radiated by a relativistic binary during the last orbiting cycles of coalescence. A standard example of coalescence for a neutron star binary \(2 \times 1.4 M\) provides the chirp signal which would traverse the sensitive band of the interferometers \((100 \div 3000) Hz\) in 2 seconds. At the current sensitivity the Livingstone detector was able to register such signals from the distance \(\sim 176Kps\) and the Hanford instrument from \(46 Kps\). So the only the Milky Way events might be overlapped in this experiment with a small contribution \(\sim 10\%\) from the Large and Small Magellanic Clouds.

The bank of templates used in this observation was modelled for variable parameters such as: \(i\)-the orbit inclination, \(\alpha\)-the initial signal phase and masses \((1 \div 3) M\). A “density” of templates was chosen so that a loss of SNR did not exceed 3%; it gave a total number of templates close to 2100. Noise characteristics were studied on the base of arbitrary selected lumps of noise playground; special sophisticated veto criteria were applied to avoid a statistical bias.

During the observational S1 run no candidates for GW-chirps were found at the threshold SNR=8 corresponded to the 90% of confidential limit. Meanwhile a Monte-Carlo simulation with an inserting of artificial chirp -signals confirmed an ability of detection of coincident events. So a final conclusion was formulated as "a new upper limit of the neutron star binaries coalescence rate for Milky Way Equivalent galaxies is \(R \leq 1.7 \cdot 10^6 year^{-1}\)" which is better then previous results but is still far from a realistic astrophysical prediction.

The designed sensitivity of LIGO set-ups would allow to overlap binaries at the distance \(\sim 21 Mpc\). Under the optimistic theoretical vision of the galactic rate of coalescence \(5 \cdot 10^{-4} year^{-1}\) \[26\] it forecasts the integral rate of chirp-events \(0.25 year^{-1}\).

c)Search for a continuous GW radiation (pulsars) \[27\].

There are several theoretical scenarios forecasting the pulsar’s gravitational wave emitting. It may be an NS-spin precession, oscillations of eigen modes, r-modes crust currents etc. but as it’s believed the more effective GW radiation would be produced by its non-zero ellipticity \(\varepsilon < 1\), which is defined by a relative asymmetry of inertia momentum in the plane normal to NS rotational axis. Available in literature theoretical estimates of the ellipticity predict as a realistic value \(\varepsilon \sim 10^{-7} \div 10^{-8}\) although for NS with a very strong magnetic field it might be several orders high \[28\]. At any case the astrophysical expectation GW radiation from galactic pulsars does not exceed \(h \sim 10^{-24}\) metric perturbation.
During the S1 run LIGO collaboration carried out a test of GW observation of the millisecond pulsar J1939 + 2134. This type of measurement was associated with long time accumulation of the narrow band $\Delta f \simeq 4 \text{ Hz}$ antenna’s output noise centred at the double pulsar frequency $2f_{ps} \simeq 1284 \text{ Hz}$. Before accumulation the raw output data were demodulated through a special time resampling and after its were undertaken to a very complex multichannel “matched filtering” procedure with an appropriate bank of templates varied through unknown parameters of the source (orbit inclination, polarisation angle and initial phase). There was no a “coincidence procedure” in this measurement of the continuos signal from well positioned source, results of all detectors were used independently and might be summed (also data of GEO set up were involved).

The lowest strain noise spectrum density of the L and H detectors in these measurements were at the level $\sim 10^{-22}$. Effective time duty cycle was $209 \text{ h}$ for the Hanford and $137 \text{ h}$ for Livingstone instruments. The upper limit for the detected amplitude of GW radiation of the pulsar J1939 + 2134 inferred from S1 run data consisted in $h \simeq (1.5 \pm 4.5) \times 10^{-22}$ (accounting for different interferometers involved). This limit does not present any new qualitative knowledge for astrophysics but it was a first time when the measurement was performed with the well defined target, - the concrete pulsar with known coordinates and frequency. Estimation of its ellipticity resulted from this upper limit also was large $\varepsilon < 3 \times 10^{-4}$ and would require a huge magnetic field $\sim 10^{16} \text{ G}$.

d) Detection of the GW stochastic background, [28, 33].

This is a very ambitious program of detection a relic GW stochastic radiation produced in a much more early universe (at the “Planck time”) then its electromagnetic analog CMBR. Such objective looks more problematic in respect of the current interferometer sensitivity comparing with the above mentioned programs. A conventional description of that background contains a special parameter $\Omega_g(f)$ which is the GW energy density per unit logarithmic frequency normalized on the critical energy of the “close universe” $\Omega_g(f) = (f/\rho_c)(d \rho_g/df)$. This parameter is related with the power spectrum of the gravitational wave strain $<h^2(f)>$ via the formula [28]: $<h^2(f)> = (3H^2/10\pi^2 f^3)\Omega_g(f)$, where $H \sim (1.5\cdot 10^{10} \text{ y})^{-1}$ is a present day Hubble constant. Thus the largest $h(f)$ corresponds to the low frequency wing of the interferometer bandwidth, so for $f = 100 \text{ Hz}$ one comes to the estimate $h(f) \sim 5 \cdot 10^{-22} \sqrt{\Omega_g} H z^{-1/2}$ with $\Omega_g \simeq \text{Const.}$ In the Standard Cosmological Model the GW relic background is considered as an isotropic, stationary, Gaussian noise with $\Omega_g \leq 10^{-8}$ [33].

A detection method consists in a measurement of the cross-correlation variable combined from outputs of two independent detectors located in the same place. Then a correlated “GW noise signal” has to be accumulated in time at the back- ground of independent intrinsic noises of both detectors. The sensitivity to the parameter $\Omega$ grows as $\Omega \sim h^2/\sqrt{\Omega_g} T$ where $T$ is the time of measurement (integration time). This ideal theoretical scheme needs a correction associated with real positions of GW-interferometers separated by a known distance. The correction factor $\gamma$ decreasing the sensitivity in the case of H and L interferometers was $\gamma \sim 0.1$ at the frequency $\sim 100 \text{ Hz}$.

During the S1 run only $\sim 100 \text{ hrs}$ of coincident interferometric strain data were
selected to establish an "LIGO upper limit" on stochastic background of gravitational radiation. With the 90% confidence limit at the frequency band $100 - 300 \, \text{Hz}$ the experimental estimation of $\Omega_g h_{100}^2 \leq 23$, where $h_{100}$ is the Habble constant in units of $100 \, \text{km/sec/Mpc}$. This new limit is not too useful for a testing astrophysical models but it is much better then the previous result from interferometers [29].

ii) Bars.

Bar detector collaborations IGEC (International world net) and ROG (Italian net) also published reports in respect of the programs mentioned above. In compare with interferometers the “bar observations” have an advantage of much more long duty cycles but a lack of narrow bandwidth. Upper limits for different type of GW signals collected with bar detectors briefly are summarised below.

In the program of short GW bursts search data of five cryogenic bars were analysed at the four year time interval 1997 – 2000 (there were three Italian set ups, one US and one Australian) [4]. A distribution of the effective observation time was the following: during 4 years there were 1319 days when at least one detector was operating; 707 days with at least 2 detectors in simultaneous operation; 173 days with 3 detectors and 26 days with 4 detectors (5 detectors practically had no the overlaping time of joint operation). In these experiments a strength of the expected GW bursts was quantified through its Fourier amplitude $h_f \simeq (1/4L^2)\sqrt{E/M \, \text{Hz}^{-1}}$ defined by $E$ - the energy deposited by a GW burst in the detector with parameters: $M$-mass, $L$-length, $f$- mean resonance frequency. Four detectors had frequencies close to 900 Hz but Australian detector NIOBE had $f \sim 700 \, \text{Hz}$. The matching filtering was performed referring to the $\delta$-pulse modelling of GW bursts.

The result of the blind search declared by IGEC sounds as “no coincidences have been found below the threshold $h_f \sim 10^{-20} \, \text{Hz}^{-1}$; at the threshold itself the registered “noise event” rate was “at least one per year”. It means a daily rate of GW bursts above this threshold has to be less than $\sim 4 \times 10^{-4}$, that looks much stronger the LIGO result. However to get an estimation of the integral magnitude of metric perturbation (used in the LIGO approach) one has to multiply Fourier amplitude to the burst’s spectrum width. For “short bursts” it is the number comparable with bar’s resonance frequency $\sim (10^2 - 10^3 \, \text{Hz})$. Also the event rate has to be corrected on the factor of “ratio of bandwidths” $\sim (2 \div 3)10^3$. Then the reduced “IGEC upper limit”: “bursts with amplitude $h \leq 10^{-18} \div 10^{-17}$ might have the rate $R \leq 1 \, \text{day}^{-1}$ and becomes comparable with the LIGO result mentioned above. At the same time a “robustness of IGEC limit” is much high the same of LIGO because the “multichannel (triple etc.) coincidences” exponentially decrease the “false alarm” error.

For bar detectors there is no a special (separate) program type of a search GW signals from binary coalescences. Due to a very narrow frequency bandwidth of these instruments such program naturally is unified with the “coincident bursts search”.

In the program of searching for periodic GW signals ROG collaboration has got the more stronger “experimental upper limit” than LIGO. In the paper [30] 2 day blind-sky search was performed with the EXPLORER’s data of 1991 year. The search was centred at the frequency $922 \, \text{Hz}$ in the band $\sim 1 \, \text{Hz}$. It resulted in the
upper limit on the order of $\sim 3 \times 10^{-23}$ with 99% confidential level. The same data were used in the paper [31] for searching periodic signals from the Galactic center in the bandwidth 0.06 Hz. For 95 days observation the upper limit of the “incoherent searching” (i.e. without any template) was estimated as $\sim 3 \times 10^{-24}$ [31].

A similar searching targeted to Galactic center was performed by the ALLEGRO detector group [32] at frequencies 896.5, 920 Hz in the band $\sim 1 Hz$. The upper limit $h \leq 8 \cdot 10^{-24}$ was found.

These results are roughly one order of magnitude stronger the LIGO one. But the principal difference is the LIGO observation was well targeted coherent search with the definite source and family of templates covering a bank of unknown spin-down parameters. Such search physically is more informative. It allowed in particular to estimate bounds for pulsar’s ellipticity (see above).

At last a limitation of GW stochastic background was also derived from observations at the bar couple EXPLORER/NAUTILUS [33, 34]; it was found $\Omega_g \leq 6 \cdot 10$ at the very narrow frequency interval 907.15 ÷ 907.25 Hz; where the factor “10” is the result of observation but the factor “6” takes into account the distance between the bars $\sim 600 km$ (i.e. it’s proportional to value $\gamma^{-1}$).

Thus one can conclude the all upper limits established in recent experiments with gravitational wave antennae are still rough for a checking of validity astrophysical models used to forecast the power and rate of expected GW events. The effective threshold of metric variations derived from these experiments was not below the level $h \sim 10^{-19}$ for the “short burst” detection and $h \sim 10^{-22}$ for continuous signals. One can wait an essential improvement of these numbers from advanced interferometers in a nearest future. Meanwhile a special strategy of observation so called a “search for astro-gravity correlation” makes it reasonable to continue experiments with available antennae even at its current sensitivity level.

### 3 Search for GW events associated with GRB

This approach is one of the more developed particular version of the common program of “searching for GW events accompanied by other types of radiation” which can be registered by parallel observational channels such as neutrino telescopes, x-ray and cosmic particles detectors [35]. The idea of such strategy is based on the general principle of optimal filtration of weak signals: the more a priori information is accessible the better a quality of detection. A modern understanding of the nature of two astrophysical phenomena, gravitational wave events and Gamma-Ray Bursts (GRB), suggests that both phenomena may have common progenitors - superdense relativistic stars at the moment of some catastrophic processes in their evolution just as binary coalescence, stellar core collapse, fragmentation etc. (see for a GW review [36], for GRB models [37], and references therein). Thus it is reasonable to look for anomalous in the output noise of gravitational detectors around time marks defined by the registered GRB. It strongly reduces the amount of stochastic data under processing compare with the “blind search” strategy and besides provides a possibility to integrate weak GW signals through an optimal summing over many GRB events. Then one may hope to discover GW-bursts even with antennae of the moderate level of sensitivity.
The problem of such parallel multichannel searching firstly was considered in [38] for bar detectors and in [39] for interferometers. In the papers [40, 41] a nontrivial problem of accumulation GW-GRB signals was analysed. The effectiveness of the accumulation directly depends on a “prior information” of the GW burst’s time position with respect to the GRB. Just in this point there is a large uncertainty of theoretical models.

Nevertheless some algorithms of the “cumulative detection” have been proposed accounting for the GRB time structure [42] and the signal processing typical for cryogenic bar detectors.

First experimental tests of checking the hypothesis of GW-GRB association are presented in the papers [43, 44]. Still no positive results were reported. The current upper limit for GW burst amplitude of this type of signal established by the ROG group is $h \leq 2.5 \cdot 10^{-19}$ [45].

4 Search for rare events

The deficit of sensitivity of the available detectors obliges experimentalists to be in the frame of program a “search for rare events”, i.e. to keep antennae in a long duty cycle relaing to a “lucky chance” of relativistic catastrophic processes in nearby region $r \leq (50–100)$ kpc of our Galaxy. This situation is similar to modern programs of neutrino astrophysics concerning a “searching for star collapse” by registering a cosmic neutrino radiation. The sensitivity of all known neutrino detectors allows a $\nu$-flux registration from sources located close then 100 kpc. Nevertheless precedents of such events had took place in last years.

The first one was occured during the SN1987A when some coincident signals registered by room temperature bars [10] were associated with neutrino bursts detected simultaneously by neutrino telescops. Despite of the very strong criticism [46, 47] this case had definitely demonstrated a reason of the “astro-gravity correlation” strategy and much more a reason to keep in continious operation detectors even of moderate sensitivity.

The second case was reported recently by ROG collaboration. Analysis a posteriori of the EXPLORER-NAUTILUS data collected in the year 2001 discovered an excess of statistically meaningfull coincident excitations [48]. The excess observed in the sidereal time coordinate was concentrated around the four hour time mark with width two hours. At this period the two bars were oriented perpendicularly to the galactic plane and their sensitivity for galactic GW-sources was maximal. The energies of coincident events deposited in each bar were approximately equal and being recalculated to the radiated energy were estimated as $\sim 10^{-2} M_{\odot}c^2$ for sources in the Galaxy center. At the same time the rate of events was too high $\sim 200/y$ in compare with conventional astrophysical forecasts. Afterwords the statistical significance of this observation was critically discussed [49, 50] but recent observations it seems confirm the first result. Detailed theoretical analysis [51] still did not lead to a definite physical explanation of the phenomenon: it looks as there would be unknown sources distributed in the galactic disc or a few (if not one) closely located invisible GW-burst repeters. An exotic supposition of GW radiation produced by primordial black hole binaries contradicts to the requirement of ho-
mogenous distribution of such objects in the Halo. Thus observations have to be continued.

5 Opto-acoustical gravitational antenna

It follows from our brief review above the current “effective upper limits” on cosmic GW pulses consist \((10^{-19} \div 10^{-18})\) in term of metric perturbation. It is interesting to note that interferometers achieved such sensitivity without a deep cooling (only advanced versions are planned to be with “cryogenic mirrors” \([52]\)). This is the result of the two technical ideas realized into constructions of these set ups. The first is the operation at frequencies apart from mechanical resonances of “high Q suspensions” where the brownian noise is strongly suppressed. The second in using the laser optical read out with a very small back action of the photon short noise: it allows to amplify the opto-mechanical transformation of mirror’s displacements by encreasing the laser power (one can remark here that up to now super cryogenic bars did not realize its potential sensitivity limited by noises of the SQUID read out \([53]\)).

This understanding was put in a basement of the Russian national project OGRAN having foreseen the construction of a room temperature bar combined with FP-interferomerter as a readout \([20]\).

The principal scheme of the OGRAN is presented on figure 1. It consists of the bar with a tunnel along central symmetry axis where a high fines FP interferometer is formed by two mirrors attached to the bar’s ends. In contrast with the optical read out developed for the AURIGA by the Legnaro group \([19]\) such construction has the expanded optical cavity with bar’s length instead of a microgap optical sensor attached at one end of the bar. This difference has a qualitative consequence: in general the responce of such combined opto-acoustical antenna must contain besides acoustical exitation of the bar also an “optical part” as a result of GW-EM interaction. A theory of this antenna was considered in \([17]\). It was concluded that in a free-mass interferometer the “optical” and “acoustical” parts were undistinguished, but for the “bar-interferometer” with mirrors following nongeodesic paths their difference has to be observable. One must to recognize the difference tends to zero in a “very long GW-approximation” nevertheless this new important feature of the combined antenna has to be taken into accout with an open mind.

A principal possibility to achieve the resolution \(h \leq 10^{-18}\) at the bar with the optical sensor was proved in the paper \([18]\). Briefly the argumentation was as follows.

The realistic sensitivity of the bar antenna for GW bursts with duration \(\tau\) is determined by the general formula

\[
h_{min} \geq 2L^{-1}(kT_n/M\omega_\mu^2)^{1/2} \cdot (\omega_\mu\tau Q)^{-1/2}
\]

where \(L, M, \omega_\mu, Q\) are the bar parameters: the length, mass, resonant frequency and quality factor; \(k\) is the Boltzmann constant. The \(T_n\) is the effective noise temperature which depends upon transducer and amplifier noises and coupled with the physical temperature \(T\) through a noise factor \(F\): \(T_n = T \cdot F\). The substitution
in the typical parameter’s values: $L = 2 \, m$, $M = 10^3 \, kg$, $Q = 3 \cdot 10^5$, $\omega_\mu \simeq 10^4 \, s^{-1}$, $\tau = 10^{-3} \, s$, $T = 300 \, K$ results in

$$h_{min} \geq 1.5 \cdot 10^{-19} \cdot F^{1/2}$$

(2)

The noise factor $F$ is defined by the ratio a real noise variance to the thermal noise variance in the antenna bandwidth $\Delta f \simeq \tau^{-1}$. For the optical interferometer read out

$$F = (2M/\tau)(G_e/G_b)^{1/2}$$

(3)

Above the spectral densities of Brownian $G_b$ and optical $G_e$ noises were introduced with the definitions $G_b = 2kT M \omega_\mu/Q$ and $G_e = B \omega_e^2 (2h \omega_e/\eta W)/(\lambda_e/2\pi N)^2$; where $\omega_e$, $\lambda_e$, $W$ are the frequency, wave length, power of the optical pump; then $\eta$, $N$, $B$ are the photodiod quantum efficiency, number of FP reflections and “excess noise factor” (number of times a real optical noise exceeds the short noise level). For the designed OGRAN optical parameters: $W = (1 - 3) Wt$, $B \simeq (1 - 10)$, $\lambda_e = 1.064 \mu$, $\theta = 0.8$, $N = (10^3 - 10^4$ one can find the estimation $F \simeq 1$, so the forecasted sensitivity (2) reduces to $h \sim 10^{-19}$.

It is important to emphasize that the formula (1) supposes a whitening of the Brownian bar noise (a cut off the bar’s resonance noise region) and operation at the “wings” of the thermal noise spectrum. A response to GW exitation out of the resonance is very small but the modern optical read out is capable to pick it up.

A practical realization of this opto-acoustical detector associated with a high frequency stability laser as a source of the optical pump. A simple direct injection of the beam into bar’s FP resonator would requier the unrealistic frequency stability according with $\Delta \omega/\omega = h \sim 10^{-19} Hz^{1/2}$. For this reason the practical scheme has to be composed as a “differential bridge” with automatic compensation a large part of frequency drifts. From the experimental optics two types of such “bridges” are known: first is the Michelson interferometer (just it was taken for the interferometric GW antennae); second is called as a “comparator of optical standards” in which one narrow frequency EM source refers to the similar one and slow drift of both might be corrected. This type of scheme was used by the Legnaro group [19] and it was choosed also as a “preferable technique” for the OGRAN set up.

The OGRAN collaboration consists of three Russian Institutions: i) Sternberg Astronomical Institute of Moscow State University, ii) Institute for Nuclear Research RAS, (Moscow), iii) Institute of Laser Physics Siberian Branch RAS (Novosibirsk). The declared goal was to install the large ($\sim 2.5$ ton) opto-acoustical GW detector into underground camera of the Baksan Neutrino Observatory (INR) and to use it in a duty cycle in cooperation with the GW world net firstly at room temperature and then in its advanced cryogenic version. ILP keeping a leading position in Russia as a center of high frequency stability optical standards developed a specific variant of the laser frequency stabilisation by a high finesse optical cavity ?? which was selected for the OGRAN set up.

A logical structure of the OGRAN measurement scheme contains a frequency coupled laser source and FP-cavity of the bar, so that oscillation of the bar’s length resulted in frequency variations of the output light beam which has to be measured by some discriminator based on a very stable external optical cavity. Idealogically this corresponds to the AURIGA optical sensor [19] but its realization becomes much more complex for the long (expanded) cavity then for the micogap one.
A first prototype of the OGRAN was developed in the SAI MSU. Its optical scheme is given on figure 3. Only small effective laser power $\sim 2 \text{mW}$ was available, so the two mirrors FP cavities were utilized with Faraday isolators instead of the “three mirrors” resonator shown at the ?? (for a large laser power the three mirror construction is preferable). In the mecanical part a small pilot model of the bar detector was manufactured with parameters: $M \simeq 50 kg$, $L = 50 cm$, $\omega_{\mu} = 2\pi \times 5 kHz$. The finess of FP-cavities of the bar and discriminator were equal $F \simeq 800$. The discriminator was thermoisolated and had a feed back loop at slow frequencies to tune a position of one mirror (attached with PZT to its end) keeping the optical resonace. Calibration experiments have shown the absolute sensitivity to the pilot bar oscillations at the level $\sim (1 - 2) \cdot 10^{-14} \text{cm/Hz}^{1/2}$; the corresponded pictures are given on ?? . The sensitivity was limited by the resonance thermal noise of the bar and approximately the same level of optical noises. This result is two orders of magnitude less the designed level $\sim 10^{-16} \text{cm/Hz}^{1/2}$.

At present a new 3 Wt single mode stabilized laser is under preparation as well as mirrors with high reflectivity $R = 0.9997$ and small losses $\sim 50 \text{ppm}$. This modification must allow to get the 1.5 orders improvement in the registering amplitude for the pilot model out of the acoustical resonance. Meanwhile big components of the real set up partly are ready (vacuum chamber, bars) partly are in progress as well as an infrastucture of the project: the underground lab in Baksan, factory hangar in SAI MSU for a test measurements with big bars etc.

The plan of development foresees (first) an operation with the OGRAN set up at the level $\sim 3 \cdot 10^{-19}$ with “room temperature bar” starting from 2006 and (second) a parallel construction of the cryogenic OGRAN version with the final goal $h \sim 3 \cdot 10^{-22}$. In this activity OGRAN collaboration hope to use a large experience and assistance of the Italian cryogenic bar group (ROG collaboration [2]).

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Our final note is sad: we should express a very deep feeling associated with the loss in a tragic accident our young, very talented colleague and co-author Andrej Serdobolskii who made a valuable contribution in the OGRAN prototype and was very good friend for us.
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Figure captions

Figure 1. Principle layout of the OGRAN detector.

Figure 2. LPF-scheme of laser frequency stabilisation:
- EOM — electro-optical phase modulator;
- DBM — double balance mixer;
- AFC — laser frequency driver;
- PD — photodetector.

Figure 3. The principal layout of OGRAN project:
- EOM — electro-optical modulator;
- 45P — polarizer;
- \(\lambda/4\) — plate \(\lambda/4\);
- FD — photodetector;
- Mrs — adjustable mirrors.

Figure 4. Spectral characteristics of OGRAN pilot model:
- a) frequency noise distribution, b) displacement sensitivity.
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