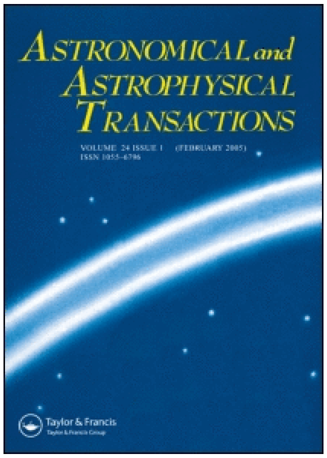

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THE STATUS OF THE GRAVITATIONAL WAVE SETUPS AT MOSCOW UNIVERSITY

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(28 December 1992)

The program of developing experimental gravitational wave research at SAI (MSU) was started in 1990 (the general perspective was reported at the Australian EFW-conference[1]). This program was declared in cooperation with Nuclear Research Institute of Russian Ac. of Sciences (NRI) and was stimulated by observational results during the SN 1987A explosion. The economical problems of our country did not permit the development of that program as it had been planned initially but nevertheless some steps have been made. In this report we present briefly the status of the gravitational setups which have been already installed and some which are in progress.

1. INTRODUCTION

It was Academician Ya. B. Zeldovich who stimulated the gravitational wave experimental research in Moscow State University in the summer 1969 just after the first Weber's reports had appeared in *Phys. Rev. Lett.*[2] It seemed at that time that the scientific world was at the threshold of discovering the gravitational wave astronomy. Zeldovich was very inspired by this perspective and drew V. B. Braginsky and one of the authors of this report into the preparation of an article where he gave his estimation of the current situation as well as of his view of the future.[3] Now looking back we can recognize that his prevision of the development of this direction in science was true in many aspects. So he pointed out to three principal relativistic sources of gravitational wave pulses from space: the oscillation of the superdense core in the process of SN explosion with associated different types of asymmetrical collapse (including falling down of a test mass to the black hole and collisions of black holes) and the coalescence of superdense binaries at the final stage of the evolution. Many authors during last twenty years published papers with analysis of these sources and at present we have a very reliable astrophysical forecast of the GW-events. Zeldovich also paid attention to the problem of a global net of gravitational wave observatories to solve the inverse problem of reconstruction the position and physical properties of the sources. During the last ten years this subject was also developed in many papers for the resonance-bar detectors as well as for the free-mass laser interferometric antennae. Zeldovich emphasized the role of gravitational wave astronomy as a unique channel of astrophysical information about internal processes in nuclei of galaxies, star clusters and black holes. There was only one point, the date of initiating GW-astronomy, where Zeldovich's optimistic forecast did not come true. The problem appeared to be much more difficult and sophisticated than he expected in 1969.

2. THE ROOM TEMPERATURE BAR-ANTENNA

A direct goal of our room "temperature bars" program was formulated initially as the search for possible correlation effects between the noise level of gravitational bar detectors and the stochastic background of the Baksan Neutrino Scintillator. Such formulation was motivated of course by the correlation events discovered after the SN 1987A explosion.[4]

The plan was to use two bar detectors with different types of transducers in parallel of the ordinary piezocrystals to separate possible false signals produced by a direct excitation of the electromagnetic part of the read-out system. We discussed the two versions: the bar detector with a tunnel current probe[5] and the other one with an optical FP-cavity.[6] In practice, both schemes appeared to be complicated enough and we continue to work on its realization.

At present we have finished assembling and tests of the bar detector with piezoelements inserted in the bar's body (at three positions around the perimeter of the central circle). This model of the bar was also machined to profile the horns (similar to the first Russian gravitational detector);[7] between the horns we planned to put a tunnel current probe as the second controlling read-out.

The parameters of this antenna are following: mass, $1.2 * 10^3$ kg; length, 1.5 m; eigenfrequency, 1623 Hz; quality factor, $6 * 10^4$; vacuum, $1 * 10^{-4}$–$4 * 10^{-5}$ torr;

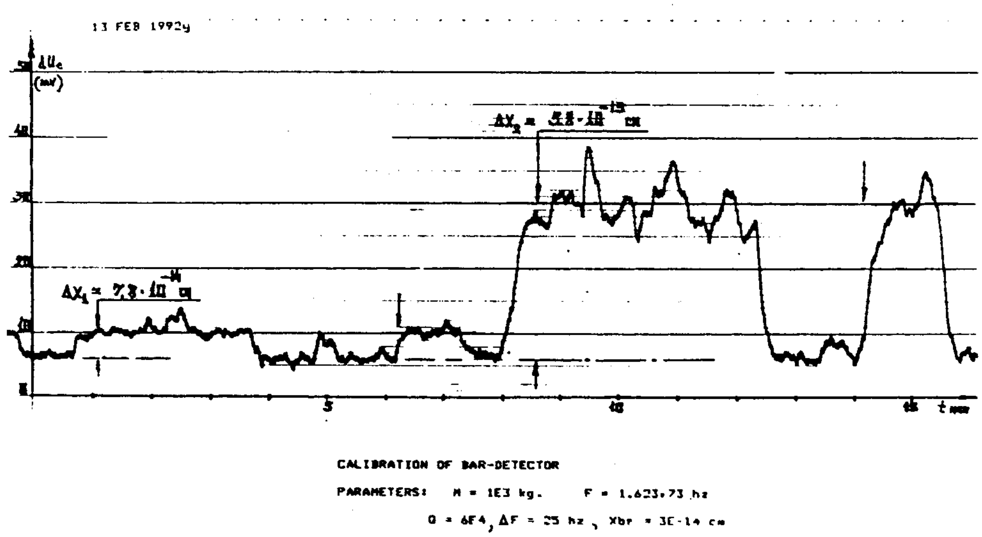
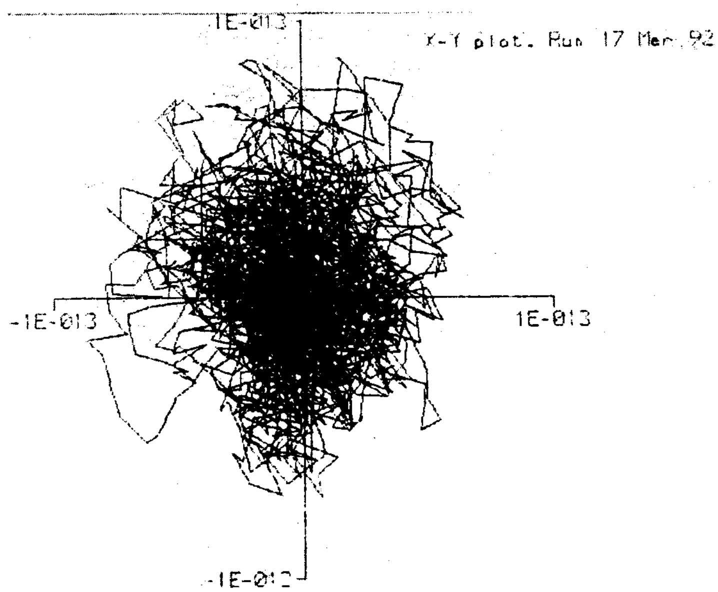
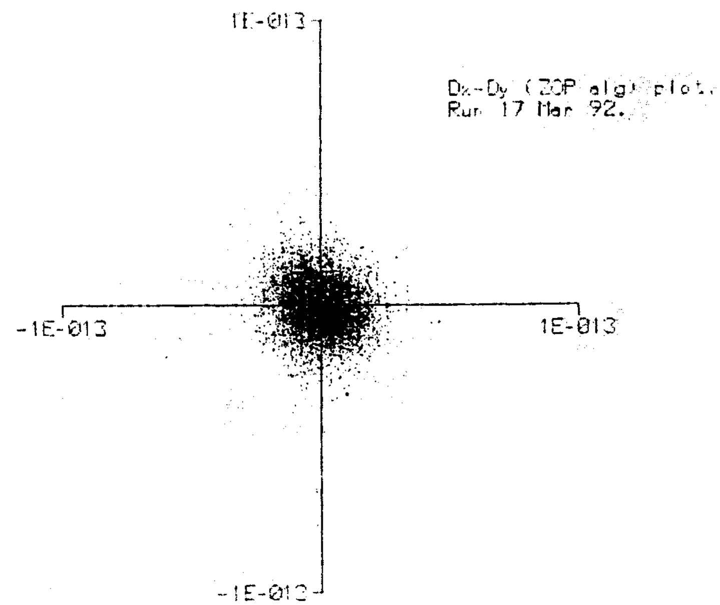


Figure 1 The calibration graph of the room temperature bar. The evolution of the forced oscillations amplitude: the small steps present the response on the calibration force induced vibrations at the level 7.8×10^{-14} cm; the large steps correspond to 5.8×10^{-15} cm; the frequency bandwidth of the electronic read-out is 25 Hz. The variations of the step's top are a result of the frequency unstability of the calibration generator.



(a)



(b)

Figure 2 The Brownian motion of the bar antenna. a) The Brownian motion of the oscillation amplitude of the bar on the phase plane; the scale on the both axes where the quadrature components of the stochastic bar's vibrations are plotted is $(1\text{–}10) \times 10^{-13}$ cm. b) The Brownian motion after optimal filtering procedure: differential link with 1 sec. delay.

e.m. transform. coefficient, $5 * 10^5$ v/cm; input preamplifier's noise, 0.6 nv/Hz$^{-1/2}$; acoustic filter's attenuation more than 200 db at the eigenfrequency. The sensitivity of the antenna was tested in a direct calibration by external force. It proved that the sensitivity level for the minimal detectable deformation is not worse than $5 * 10^{-17}$ 1/Hz$^{-1/2}$ (Figures 1 and 2).

In data processing we follow the standard procedure extracting the quadrature components with the help of a reference frequency standard tuned to the bar's eigenfrequency. Our nearest goal is to work out the process of a long time observation and data collection, then to put antenna in duty cycle at the beginning of 1993. We realize also that it would be necessary to develop a convenient procedure to compare the bar's noise with the background of the Baksan Neutrino Scintillator.

3. OTHER FACILITIES

As mentioned above, we continue to work on the construction of the tunnel current probe which is now placed on a small test-model of bar (50 kg, 50 cm). Though the electronic supply system for this transducer is not trivial, the main problem arises with the mechanical sensor unit containing a needle under plane surface with the gap of order 10 angstrom. In this unit it is very difficult to avoid redundant noises of both mechanical and electronic nature. Another sensor, the optical FP-cavity, worked out now also on a small bar-model (50 kg, 50 cm). This model has a tunnel along the central axis and the confocal mirrors attached to the bar's ends. With a standard stabilized laser of the ordinary power of 10 mW on this model, it is easy to achieve the resolution of $1 * 10^{-13}$ cm/Hz$^{-1/2}$. At present we try to improve this result by two order of magnitude.

A large bar detector with a central tunnel has been also already prepared ($m = 3.5$ T, $l = 2$ m) and a large vacuum chamber with antiseismical suspension system is in assembling. This large antenna with a FP-cavity sensor is planned to be installed underground at the Baksan Neutrino Observatory.

It is worth to note here that our plan to use the new types of transducers has two objectives. The first, which was already mentioned, is to have a possibility to remove some false signals induced by direct disturbances in the electromagnetic elements of the transducers The second reason is more refined: as analysis has shown[5,6] that these types of transducers possess a reduced value of the back-action, so increasing the coupling between the bar and the transducer can result in decreasing the antenna's equivalent noise temperature and yield the sensitivity level for measurable deformations of $1 * 10^{-18}$ l/Hz$^{-1/2}$ which is typical of the helium-temperature resonance bar antennas.[8]

4. THE CRYOGNIC BAR-DECTOR

In cooperation with the Solution Refrigerators Division of the "Helium Mash" Industry Institute (Dr. Amamchian, R. G. and Dr. Kotov, L. E.) we have developed a cryostat based on a closed H3-cycle and one test model has been manufactured. It permits to cool a bar detector with the mass of 100 kg and the length of 1 m to the temperature 0.3 K. The potential sensitivity of the bar detector under such conditions has to be at the level of $2 * 10^{-18}\,1/\mathrm{Hz}^{-1/2}$. Using these facilities we are planning to work out the technique of low temperature read-out systems (squid, etc.) and the technique of a long time keeping of the operation regime. As for a large cryogenic antenna, we have discussed the possibility to join the Italian Project "Nautilus" with support from the Italian side. We expect that the situation will be more clear at the beginning of the next year.

5. THE BAKSAN LASER INTERFEROMETER

Our second setup, the long-base laser interferometer-deformograph, has been installed in the main tunnel of the Baksan Neutrino Observatory.

It is the Michelson-type interferometer but with unequal arms. The measurable arm lies along the tunnel and has the length 75 m. The second reference arm is 0.3 m long. The mirrors and the beamsplitter are placed in vacuum tanks, which are installed on concrete foundations untied from the general tunnel's bottom and rigidly connected only with the fundamental rock. One tank carries the input and output windows, the short arm and the beam splitter. The other tank contains only the end mirror. The tanks are joined by tubes 0.3 m in diameter with three bellows in connecting points.

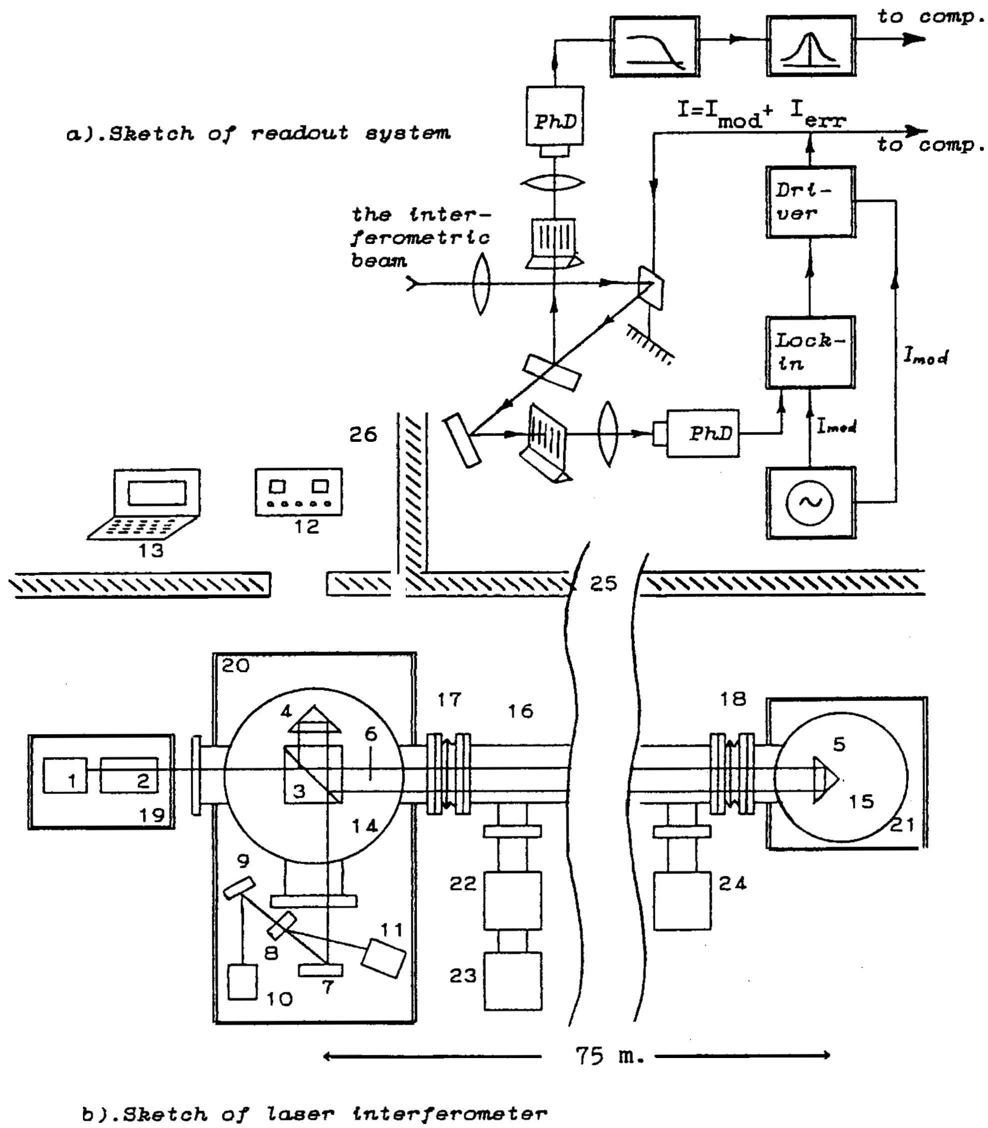
Three different kinds of pumps provide the operation vacuum at the level of $1 * 10^{-5}$ mbar (with additional eight magnetodischarge cooling pumps, one can achieve $1 * 10^{-7}$ mbar).

The optical scheme we use at present is a simple Michelson-type one (with one round-trip for beams in each arm). Besides, there is a technical possibility to utilize an optical delay line with 30 bounces in the large arm. We use the beam from a commercial frequency-stabilized He–Ne laser with the power 10 mW which passes through a telescopic system before falling at the input window of the interferometer.

It is obvious that our interferometer, being first of all a geophysical instrument, fits to measure the deformations between two points of the earth crust.[9] But it is absolutely true only for low frequencies. For a high-frequency range of order (1–10) kHz, this setup could be considered also as a free-mass gravitational antenna because the longitudinal elastic eigenfrequency of the mirrors attached to the rock is much less than 1 kHz. The question of our interests then is the value of residual seismic noises in that region. We hoped that the level of these noises would have been small enough to provide the resolution of the order of $1 * 10^{-16}$ in terms of deformations. In other words, it would be at the level of the sensitivity of a room temperature bar antenna.

Taking into account this goal we have choosen a specific read-out scheme which permits to follow simultaneously relatively large slow variations of the earth crust and very small perturbations of the seismic noise level at high frequencies around 1.6 kHz.

The read-out system operation is based on the modulation of the displacement of interference fringes relative to the chink of the photodiode (the block scheme is presented in Figure 3). The output interferometric pattern, after reflection from the modulator's mirror, goes through an artificial diffraction pattern and falls onto



1. He-Ne laser; 2. telescopic system; 3. beamsplitter; 4,5. end mirrors; 6. wedges; 7. modulator; 8. semitransparent mirror; 9. plate mirror; 10,11. photodiodes; 12.electronic equipment; 13. computer; 14,15. vacuum tanks; 16. vacuum tubes; 17,18. bellows; 19,20,21. concrete foundations; 22,23,24. vacuum pumps; 25. tunnel's main wall; 26. room for equipments and operators.

Figure 3 Sketch of the laser deformograph and the electro-optical read-out system.

the photo-diode. The modulator, which is the galvanometer's mirror, is driven by two identical signals: the first one is the 20 kHz frequency modulation signal and the second one is the signal of the feedback system which keeps the "dark spot" position of the interferometric pattern on the chink of the photodiode. The "dark spot" position is produced by the crossing of the output interference picture with the artificial diffraction pattern in the zero phase. The variation of the measurable arm lengths of the interferometer leads to the displacement of the interferometer pattern. The feedback signal formed by electronic equipment compensated this displacement by turning the modulator's mirror. This signal is also the interferometer output signal whose phase and amplitude carry information on the direction and value of displacement, respectively. This is the so-called "geophysical channel" of information (the bandwidth 0–500 Hz).

A part of the output light is directed to the second photoreceiver through another diffraction pattern shifted by one fourth part of the wavelength with respect to the interferometric pattern. The electronic response of the receiver filtered at the first stage in the bandwidth 500–2000 Hz and at the second stage, in the bandwidth of about 20 Hz around frequency 1.62 kHz presents the second channel of information, the so-called "astrophysical channel".

Of course, the dynamic range of the feedback circuit is restricted, however it can be regulated. The typical range of values we used is two or three fringes, i.e. (0.6–0.9) mkm. For larger perturbations the feedback was destroyed and the system jumped into a new equilibrium position.

During data processing the jumps can be removed and a continuous realization of the output signal can be reconstructed. The characteristic time of the feedback system is determined by the subsidiary modulation frequency which is 20 kHz. Some illustrations of the interferometer in operation are presented in Figs 4–6. Figure 4 presents a computer-processed output signal of the geophysical channel. The frequency range of the record is limited from above by the cut off frequency

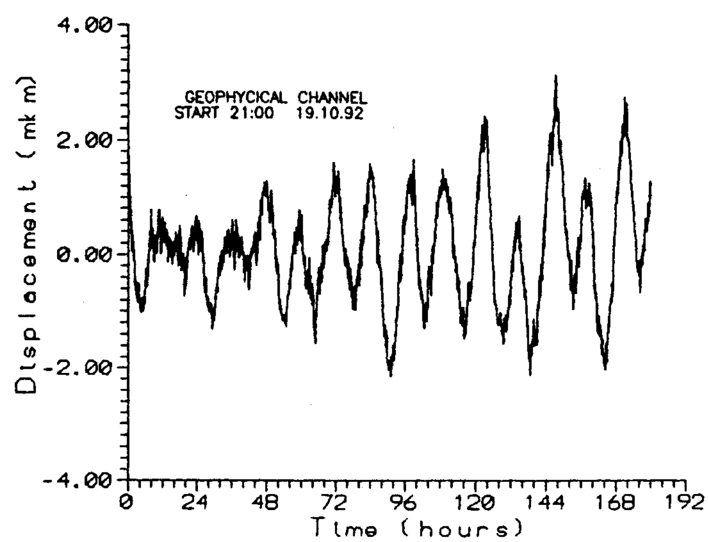


Figure 4 The geophysical channel: the experimental data in real time.

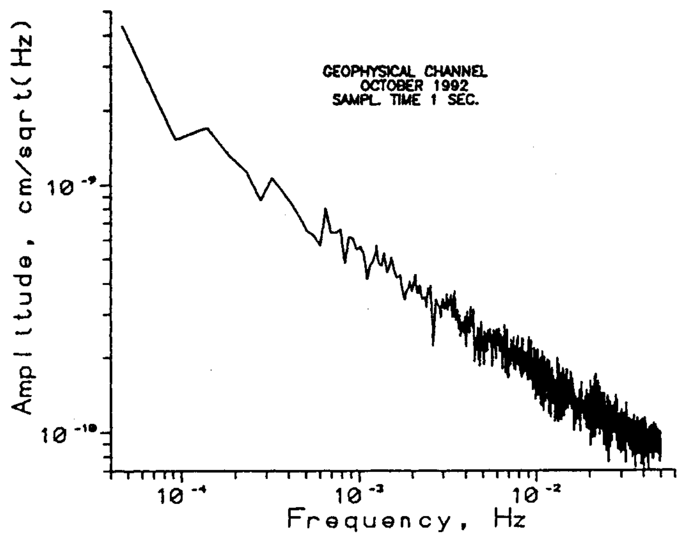


Figure 5 The mean noise spectrum of the geophysical channel.

0.1 Hz. This graph of eight days length demonstrates a tidal perturbation of the earth crust against the background of a slow drift. The main tidal harmonic (the longitudinal differential component of the crust deformations) has the period about 12 hours and the amplitude of order 2–3 mkm.

The measured noise in the frequency range from 10^{-4} Hz to 0.1 Hz is shown in Figure 5 expressed as the spectral density of the equivalent mirror displacement (the axes have a logarithmic scale). The behavior of the noise corresponds to a flicker-noise in this frequency region. In the frequency range 10^{-1} Hz the

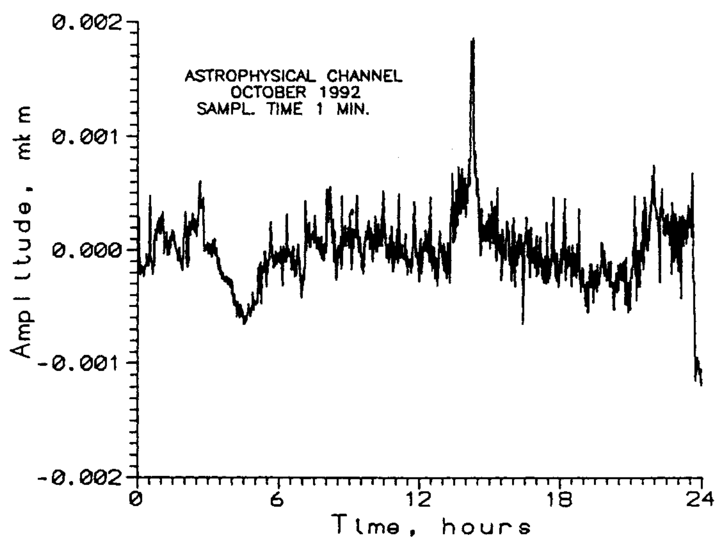


Figure 6 The envelope of a high frequency signal in real time.

experimental sensitivity of our installation is about $10^{-10}\,\mathrm{cm/Hz^{1/2}}$, which corresponds to the strain sensitivity of $10^{-14}\,\mathrm{Hz^{-1/2}}$.

Figure 6 presents the envelope of the output signal of the astrophysical channel in real time in the range (1620 ∓ 40) Hz. The extrapolation of the $1/f$-law (from the low frequency region) to the region (1–2) kHz predicts the decrease of deformation noises to the level below $1 \times 10^{-16}\,\mathrm{Hz^{-1/2}}$, but the question is the level of tails of the industrial (technical) noise. Our nearest goal is the direct measurement of this noise. We hope that the total residual deformation noise of the astrophysical channel around the frequency 1,623 kHz (the fundamental frequency our bar detector) will not exceed the level of $1 * 10^{-16}\,\mathrm{Hz^{-1/2}}$, which corresponds to the sensitivity of a room temperature bar antenna.

6. PLANS OF DEVELOPMENT

During the last few years the room temperature gravitational bar antenna was prepared by the group of our Laboratory by the researchers Melezhnikov, I. V., Oreshkin, S. I., engineers Ztyganov, A. V., Ztepkov, A. N., Trifonov, D. V. and technician Motylev, A. M. The Baksan Interferometer was installed and assembled by the researchers Dr. Klychko, B. S., Kravchuk, V. K., Melezhnikov, I. V. and engineers Buclersky, A. M. and Myasnikov, A. V.

The first objective of our activity during 1993 is to carry out a coincidence experiment including our two setups: bar antenna and interferometer and also the Baksan Neutrino Scintillator with searching for some correlations effects. On the way we have also a secondary objective to search for any correlations between the dynamics of slow crust deformations measured by the interferometer and the variations of the general radioactivity background.

Other plans strongly depend on our funds in next years. In any case, we believe that it will be possible to achieve a progress with the following setups: the room temperature bar with optical FP-cavity and the small cryogenic bar (100 kg). We plan also to finish our with preparation of the tunnel current probe and to install it on the profilized room temperature bar.

As a further step we consider the realization of a project of one hundred meters Michelson-type interferometric gravitational antenna with one thousand bounces for laser beam and the sensitivity level of the order of $1 * 10^{-21}$–$1 * 10^{-22}\,\mathrm{Hz^{-1/2}}$.

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