

OBSERVATIONS OF THE EARTH'S DEFORMATION SPECTRUM BY MEANS OF A LASER INTERFEROMETER-DEFORMOGRAPH

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Long-term observations of lithospheric deformations were carried out in the frequency range of 5×10^{-6} to 10^3 Hz in the Northern Caucasus at the Baksan Geophysical Observatory (Shternberg Institute of Astronomy). Observations were made by means of an underground laser interferometer-deformograph with a baseline of 75 m. The obtained estimate of the spectral density of deformations determines the background level of seismic noise over a wide frequency range.

Long-baseline laser interferometers are the most perfect instruments for measuring relative changes of distances between two points. The frequency range of laser interferometers practically begins from zero and is bounded from above only by the fast-response of the electronic devices used, which may, in principle, be tens of megahertz. The dynamic range of long-baseline laser interferometers is also practically unlimited and the threshold of sensitivity to relative changes in distances exceeds that of other instruments by several orders of magnitude. An important advantage of laser interferometers is the presence of an internal length standard, which is the wavelength of laser radiation known with a high degree of accuracy.

The above-indicated properties of long-baseline laser interferometers make possible their use as deformographs for the solution of a wide range of fundamental and applied geophysical problems [1-8].

The northern part of the Great Caucasus Ridge is one of the most active in geodynamic respect among the Russian regions characterized by intensive movements of the Earth's crust. Of special interest is the Elbrus Mountains bounded from the North by the Tyrnyauz depth fault zone. The thickness of the Earth's crust here is 60 km and is the largest within the Caucasus [9]. On the whole, the seismic activity of this region, apart from the longitudinal fault, is due to still continuing uplifts and arch-like folds of the Earth's crust in this zone.

In this region, the Shternberg Institute (Moscow University) has at its disposal an underground geophysical observatory equipped with a laser interferometer-deformograph and a two-coordinate pendulum tiltmeter. The observatory is located in Kabardino-Balkaria, in the Baksan ravine (settlement Neitrino) 30 km to the south-west of Tyrnyauz and 25 km from the Elbrus Mountain. The interferometer is mounted on the 650-m level at a depth of 400 m along the Glavnaya drift of the Baksan Neutrino Observatory (BNO) of the Institute of Nuclear Studies (Russian Academy of Sciences) driven into the mountain massif (the Andyrchi mountain) to a distance of 4200 m (Fig. 1). The coordinates of the interferometer are: latitude, $43^{\circ}12'$; longitude, $42^{\circ}43'$; and azimuth, $150^{\circ}37'$.

The location and equipment of the laboratory provide good conditions for carrying out investigations of lithospheric deformations and seismic vibrations at a new (with respect to the sensitivity threshold) level over a wide frequency range. The setup makes it possible to record, in the monitoring regime, changes in the stressed state of the Earth's crust during the entire period of observations; to measure diurnal and semidiurnal tidal strains and the dynamics of their variations in time; to study the entire spectrum of the Earth's vibrations and also the range of superlong-period vibrations (periods ranging from 1 to 6 h), which has been studied little.

The study of the correlations of weak lithospheric deformations with earthquakes can make a con-

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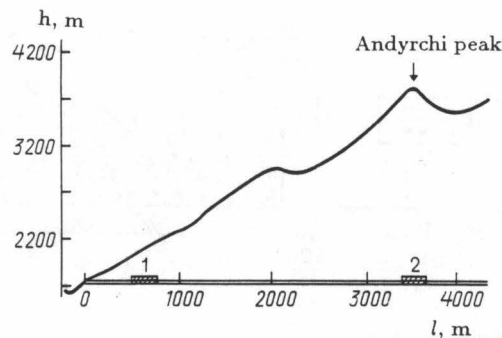


Fig. 1

Cross section along the axis of the BNO main drift: (1) scintillation neutrino telescope and interferometer; (2) Ga-Ge neutrino telescope.

tribution to the problem of forecasting earthquakes since, according to current concepts, the detection of deformation precursors is a very promising method.

On the whole, the recording of lithospheric deformations and seismic vibrations by means of a long-baseline laser interferometric setup will make it possible to extract qualitatively new information about the Earth's structure and the dynamics of its interior.

1. THE INTERFEROMETER

The optical system of the interferometer is a double-pass ($N = 2$) Michelson unequal-arm interferometer operating in the split-beam regime produced by using angled reflectors as reflecting plates. Operation by the split-beam scheme somewhat increases the overall size of the optical system and the waveguide, but the optical bypassing is easily attained, which prevents the reflected radiation to return to the laser. Thus, no additional optical gates are required. The length of the major (measuring) arm of the interferometer is equal to 75 m (the length of the optical path is accordingly 150 m) and that of the minor (reference) arm is 0.3 m.

The light source used is a frequency-locked He-Ne laser (model LGN-303), which operates in two orthogonally polarized radiation modes. The radiation wavelength is $0.63 \mu\text{m}$, the power output is 2 mW, and the relative instability of the laser radiation frequency is not worse than 10^{-9} during 8-h continuous operation.

Figure 2 shows the general functional scheme of the interferometer. The laser radiation (1) arrives at a telescopic system (2) formed by two lens. At the focus of this system there is a diaphragm for cutting-off higher diffraction orders (magnification of the system $\Gamma = 25$). The telescopic system produces a beam waist on the far reflector of the interferometer. The beam formed by the telescopic system, which has a wavefront with a large radius of curvature, gets at the beam-splitter (6), which splits the beam into two parts and directs them to the measuring (19) and the reference (4) angled reflectors. The reflected beams are deflected at a small angle with the aid of an optical wedge (5) and recombine at the same beam-splitter (6). The interference pattern brought about by the recombination of the reference and measuring beams consists of straight-line fringes.

The optical parts of the interferometer are assembled in two vacuum cylindrical chambers. The chambers are connected by means of three bellows and vacuum tubes of diameter 30 cm, which form a light guide. Thus, the optical arms of the interferometer are fully evacuated.

The vacuum pumping system of the interferometer consists of two parallel cells, and the vacuum in the space of the interferometer is provided by their alternate switching off. The total pumped-out volume is of the order of 6 m^3 . The pressure in the system under stationary conditions is $5 \times 10^{-5} \text{ mm Hg}$.

The radiation unit (laser and telescopic system) and the vacuum chambers containing the optical cells of the interferometer are mounted on three independent footings. The optical cells of the interferometer are rigidly attached to the rock by means of mechanical structures and load-bearing foundations and are not in direct contact with the drift.

The electronic recording system provides the operation of the interferometer over a wide frequency range: from ultralow (limited only by the length of continuous observations) to several thousands of hertz.

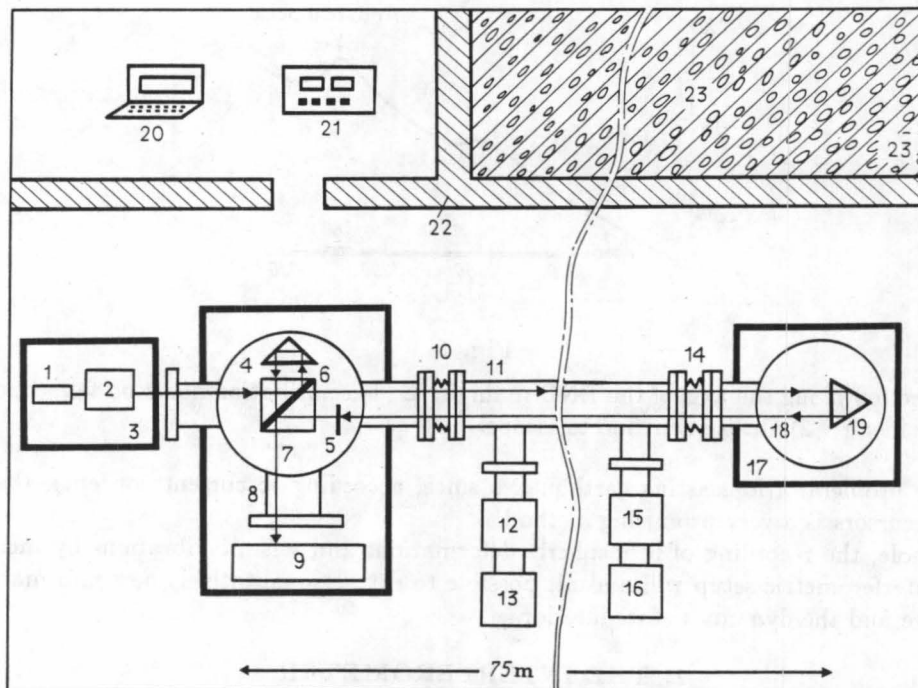


Fig. 2

Baksan laser interferometer: (1) He-Ne laser; (2) telescopic system; (3), (8), (17) isolated concrete foundations; (4), (19) angled reflectors; (5) optical wedge; (6) beam-splitter; (7), (18) vacuum chambers; (9) photodetector-modulator block; (10), (14) bellows; (11) evacuated light guide; (12), (13), (15), (16) vacuum pumps; (20) computer; (21) electronic recording unit; (22) main wall of the drift; (23) rock.

The main part of this system is an interference-fringe-tracing system of the compensation type with internal modulation.

The data-retrieval, primary-information-processing and experiment-control system is based on a 16-digit analog-digital transducer and an IBM PC-AT 286 computer, which operate in the regime of continuous monitoring of geophysical information and recording on rigid computer disks.

2. RESULTS OF OBSERVATIONS

The first observations with the above-described laser interferometer were carried out in 1992. Since the beginning of 1993 the interferometer has been operating in the regime of continuous monitoring of the Earth's deformations. Some preliminary results of estimating the observed spectrum of deformations have been published in [10]. In 1992 we carried out trial synchronous observations of superlong-period lithospheric deformations by means of two laser interferometers: the Baksan and the Sevastopol interferometers [11].

Figure 3 shows an averaged estimate of the spectral density of deformations in a frequency range of 5×10^{-6} to 10^3 Hz.

The estimates were based on experimental data obtained during the period from March 7, 1993, to January 9, 1994. The effective observations during this period made up 6327 hours, i.e., 86.4% of the entire calendar time. Spectral analysis was made using the periodogram technique with the aid of a fast Fourier-transform apparatus. The spectral density of deformations was calculated by the conventional technique (averaging over a large number of segments with 50%-overlap and multiplication of the segments by the Kaiser window function) in four different frequency ranges and, accordingly, for four different quantization intervals (Table 1).

The spectral density in the first frequency range was estimated by using the entire set of observations indicated, which were obtained in the standard operating regime of the interferometer. A preliminary analysis

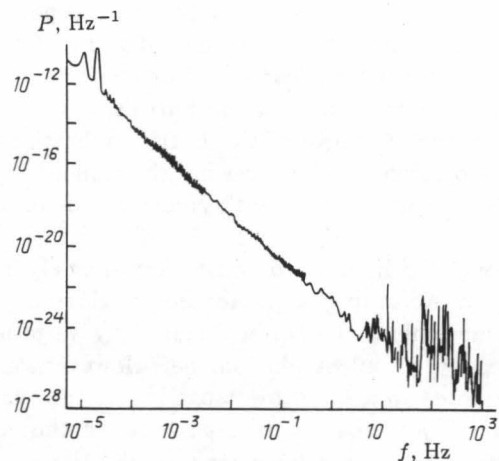


Fig. 3

Spectral power density of the Earth's crust deformations.

Table 1

Parameters of the Spectral Power of Deformations

Frequency range, Hz	Quantization interval, (s)	Number of segments of averaging
5×10^{-6} to 3×10^{-3}	180	85
3×10^{-3} to 0.25	2	960
0.25 to 50	1×10^{-2}	960
50 to 1000	5×10^{-4}	320

included recording of a low-frequency drift, band digital filtration in a given frequency range, and increasing the quantization interval from 2 to 180 s.

The spectral density in the remaining three frequency ranges was estimated by carrying out special experiments which included recording of information from "open" outputs of geophysical and astrophysical channels and the use of analog band filters of the corresponding ranges. The preliminary processing involved stages analogous to the first range.

The general pattern of the resultant spectrum corresponds to the flicker behavior of noises, and the power spectrum decreases from 10^{-12} Hz^{-1} for frequencies of about 10^{-5} Hz to 10^{-28} Hz^{-1} at frequencies of about 10^3 Hz . There are two well-pronounced maxima corresponding to diurnal and semidiurnal tidal waves, the spectral peak of the semidiurnal wave being higher. Experimental estimates of the averaged deformation amplitudes for the diurnal and semidiurnal constituents are 1.28×10^{-8} and 1.47×10^{-8} , this being in good agreement with the tidal strain amplitudes recorded in the USA in a region which is also remote from the sea (1.2×10^{-8} and 1.7×10^{-8}) [12]. At the same time, the tidal deformations recorded by a laser deformograph on the coast of the Sea of Japan are higher by an order of magnitude [4]. The ordinary (theoretical) values of tidal deformation amplitudes calculated for the location of the Baksan interferometer (assuming the Earth to be spherically uniform and the Love and Shida numbers h and l to be, respectively, 0.6 and 0.07 [1]) are 0.54×10^{-8} for O_1 and 0.97×10^{-8} for M_2 , which is somewhat lower than those observed. This difference may be accounted for by the location of the interferometer near the fault zone.

The frequency range from 5×10^{-5} to 10^{-3} Hz has been studied insufficiently. This range covers the

Earth's vibrations which have come to be known as superlong-period, in particular nuclear vibrations. For models with large values of density in the Earth's center there exist forms of nuclear vibrations with periods longer than one hour. Some calculations predict nuclear vibrations with periods of 76, 85 and 100 min and larger. However, the amplitudes of nuclear vibrations at the Earth's surface must be extremely small [13]. There are observations which point to the existence of the Earth's vibrations with periods exceeding one hour [4, 5, 7, 13, 14]. Nevertheless, the possible noise sources in this frequency range—such as slight variations of atmospheric pressure, the motion of ground waters, and thermoelastic deformations—may mask the Earth's superlong-period vibrations.

The noise in the seismic belt (from 10^{-3} Hz upward) varies very strongly in time and space. The sources of such noises depend on the frequency. According to [2], for frequencies ranging from 10^{-3} to 0.05 Hz the appearance of noise is due to deformations of the surface caused by variations of atmospheric pressure. The strongest fluctuations are caused by turbulent phenomena. However, the intensity of these noises is attenuated with depth. It should be noted that the same range covers the spectrum of the natural Earth's vibrations, whose amplitudes considerably increase during powerful earthquakes. In the range of 0.05 to 0.5 Hz, the main noise source is microseisms. For frequencies from 0.5 Hz and higher, the noises are caused by bulk waves and also by local sources of artificial and natural origin. Figure 3 shows that, against the background of the overall decrease of power, its dispersion increases in the frequency range of 10–500 Hz, which seems to be accounted for by the technogenic nature of noises in this range.

Because of the long duration of the series of observations (10 months), on which the estimation of spectral density was based, it may be treated as the background level of seismic noise in a wide frequency range. Thus, the resultant estimate of the spectral density established the lower threshold for the possible detection of geophysical signals in the region studied.

Figure 3 illustrates the unique capabilities of the laser interferometer with respect to both the frequency and the dynamic range, which makes its application expedient for the solution of a wide range of geophysical problems.

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