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Features of tidal deformations before strong distant and closely spaced regional earthquakes

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Abstract. The article presents the data of deformation monitoring implemented in the Baikal Rift Zone in the time of initiation of strong earthquakes using the heterodyne laser deformograph. The anomalous behavior of the semidiurnal tide wave amplitude before the region-scale earthquakes is described.

1. Introduction

The Earth crust is an active medium in which mechanical deformation waves continuously originate and propagate within a wide range of vibration periods. Different physical processes on the surface and underground show themselves as seismic, free, tidal, seasonal and induced vibrations creating a complex space–time structure of a nonstationary deformation field. The integrated applied research into deformation vibrations is connected with the problems of prediction of such disastrous events as earthquakes, rock bursts, volcanic activity, etc.

Understanding importance and relevance of high-precision equipment to be used in the studies of deformation processes spurred creation of an original two-coordinate laser deformograph at the Institute of Laser Physics. This equipment allows long-term and continuous detection of small deformation displacements in rocks at a relative sensitivity of 10^{-9}–10^{-10} in a wide frequency range in mine conditions at a spacing up to 100 m [1].

2. Laser deformography system

The equipment and procedure developed at the Institute of Laser Physics for the continuous precision measurement of deformations in the Earth's crust is persistently subjected to upgrading aimed to improve sensitivity and reliability. The basic operating principles of the equipment remain unchanged. The functional configuration of the deformation measurement system is shown in figure 1. The system includes a heterodyne interferometer composed of four independent optical channels three of which are measurement channels and one is a reference channel. The channels are based on an asymmetric Michelson interferometer; the reference beam from the heterodyne laser is offset with respect to frequency by 1 MHz relative to the sample beam to a displacing object. The operating principle of the measurement channels is based on the continuous recording of time history of wave phase due to the

Doppler effect under the beam reflection from the displacing object. Both measurement arms have a length of 25 m.

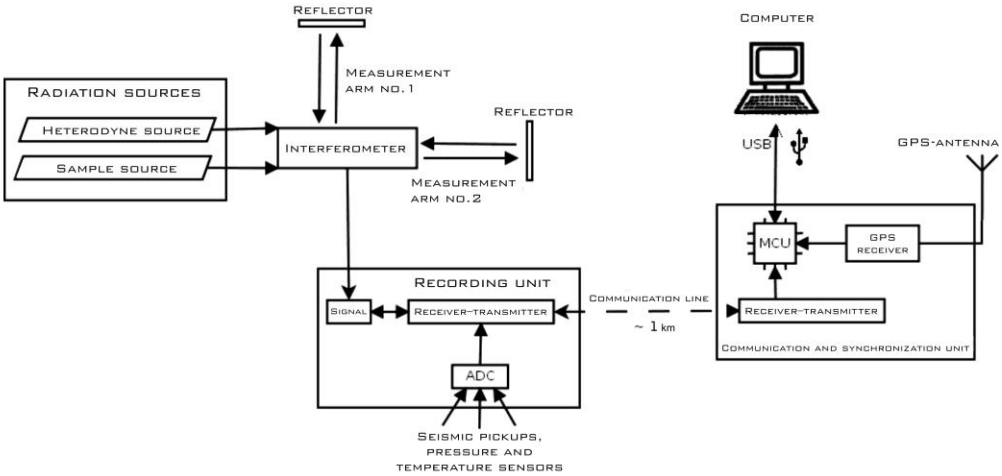

Figure 1. Functional configuration of the heterodyne laser deformography system.

The key feature of the deformograph is the absence of sampling radiation shielding from the action of atmospheric perturbations causing variation in the refraction index of air. To this end, the interferometer has, alongside two recording channels, an optical channel to neutralize atmospheric effects and frequency instability of the lasers. The optical channel includes a rod made of alloy 36N (invar) 1.2 m long with a thermal expansion coefficient $dL/dT = 8 \cdot 10^{-7}$ deg^{-1}. The signal obtained using the neutralization arm is proportional to variation in the laser source wavelength and in the mine air refraction index, and is independent of rock mass deformations. Such approach allows overcoming the major constraint of wide application of laser deformographs in geophysical surveys, namely, resource-hungry continuous-service evacuated beam guides tens meters long.

Computer-aided recording of signals is carried out at a sampling rate of 0.5 Hz. This system ensures reliable recording of small displacements in a wide range of vibration periods from 10^0 to 10^7 s, as well as allows recording of free and tidal vibrations of the Earth, deterministic diurnal variations in micro-deformation noise and features of deformation processes accompanying seismicity.

The site for introduction of the new-modification deformograph and testing of measurement procedures is situated nearby the south-west coast of the Lake Baikal. The Baikal region is selected owing to its seismic activity in the form of numerous earthquakes of different energy classes within a year. The deformograph is installed in the Talaya seismic station tunnel. Continuous recording of deformation process started more than 20 years ago. Over this period of time, the deformation measurement system has proved to be a reliable, high-precision and unfussy instrumentation for deformation monitoring of lithosphere [2]. The long-term observations reveal that the signs of seismic events in the behavior of a deformation signal are greatly governed by two parameters – energy class of an event, K, and distance to the event source, S. During initiation of seismic events with K = 13–14, the signs in the deformation behavior of the crust appear at a distance up to 100 km; for the events with K = 10, such signs can be observed at a distance of 20–30 m.

3. Features of tidal deformations during initiation of seismic events

As it was mentioned above, the high-priority objectives of deformographic monitoring is the analysis of dynamic processes in the crust before a seismic event. A peculiar place among the deformation processes of interest belongs to the lithosphere tides as they can trigger both rock bursts and earthquakes (including induced events). Tides considerably contribute to mass transfer in the Earth's interior [3], which governs evolution of stress state of the crust [4]. Fundamental harmonics of a tide signal are diurnal and semidiurnal tide waves. Their amplitudes depend on the stiffness of the crust rocks, as well as on the mutual location of the Sun and Moon relative to the Earth. Stiffness and density of rocks are governed by rock mass stresses in a general case. The diurnal tidal harmonic is distorted due to daily variations in meteorological parameters, as a rule; for this reason, it is simpler to analyze the semidiurnal tide harmonic.

The differences and the behavioral features of tidal deformations before a seismic event were continuously monitored and recorded starting from the earliest introduction of the deformography system. By way of illustration of a "tidal abnormality" in a deformation process, figure 2 presents the 10 days-long deformographic record. The deformation curve in the figure clearly shows the devastating Kobe Earthquake on 16 Jan 1995 (10:52 UTC) and the abnormal tidal oscillations 1.5 days before the seismic event.

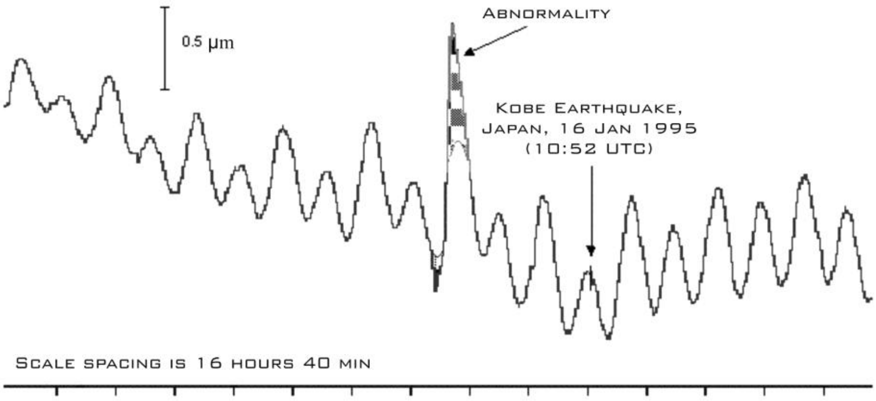

Figure 2. Fragment of deformographic recording of the Kobe Earthquake.

Similar nonstationary perturbations inside a natural deformation process in rocks, including tidal vibrations, were many times observed a few days before large planetary earthquakes, including the Spitak Earthquake in 1988 and the earthquake that hit the eastern coastal line of the Honshu Island in 2011. In view of the large distance between the laser monitoring station and the foci of the strong earthquakes, an attempt was made to explain the mechanisms of the recorded abnormalities based on the assumption that the phenomenon was of the planetary nature and connected with the interaction between the earthquake foci and the solid core of the Earth. However, until reliable comparable data are synchronously recorded by mutually remote geophysical stations, the question on the mechanism of this phenomenon remains open-ended.

Another class of periodically recorded tidal abnormalities are the signs of regional seismic events in the form of the long-term alteration of deformational response of the crust to the Moon/Sun tides by way of the change in the amplitude of an envelope of a semidiurnal tide in the same arm of the deformograph. An example of such behavior is the deformation process dynamics in the period of initiation and release of the Kultuk Earthquake on 27 Aug 2008, which was the largest earthquake in the neighborhood of the Talaya seismic station for the whole monitoring time. The epicenter of that earthquake with the energy class K = 15.5 located in the south of the Baikal lakeside at the distance S = 30 km from the seismic station. Due to the high energy class and relatively short remoteness from the observation station, the earthquake was a rare and very valued event for the analysis. In terms of the earthquake, the features of geodynamic effect of a close-spaced large earthquake on deformation process in the curst were demonstrated in [5]. Amongst deformation signals related with the initiation of a closely spaced earthquake, the anomalous behavior of the amplitude of the semidiurnal deformation tide in the East–West direction was described. That abnormality showed itself as a jump by 20–30 % in the deformation response of the Earth's crust to the joint gravitational tides of the Moon and Sun three days before the Kultuk Earthquake and the subsequent relaxation of the abnormality within a few days after the event.

The described feature is illustrated in figure 3: the curves A and B show the tide wave trains in two measurement arms of the deformograph after filtration in the range of 708–768 min (the lighter shade is the East–West arm, the darker shade is the North–South arm). The amplitude of this signal changes with a period of 14 day approximately depending on the position of the Sun and Moon relative to the Earth. The tide has the maximum amplitude when the Sun, Moon, Earth centers and the monitoring station lie in the same plane. It is seen in the figure that the East–West tide amplitude is smaller than the North–South tide amplitude, which agrees with the theory. However, in the time zone closer to the Baikal earthquake, the effect is opposite. Three days before the seismic event in question, the tide amplitude is noticeably higher in the East–West line than in the orthogonal direction. This fact is also visible in the enveloping curves C and D.

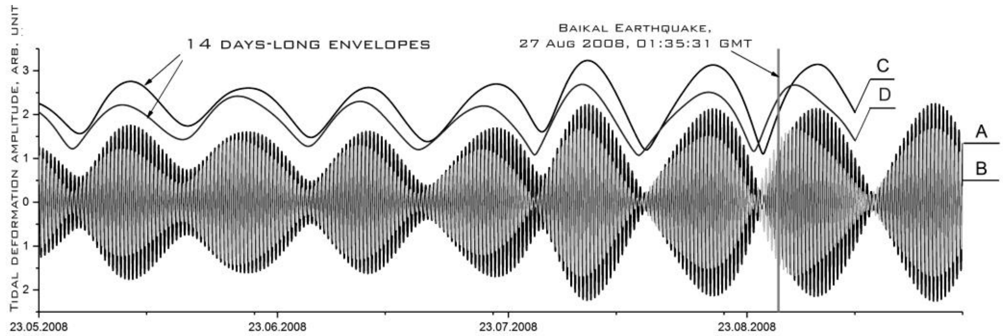

Figure 3. Semidiurnal tidal harmonics in the orthogonal arms of the deformograph and the enveloping curves.

The first half-plot visualizes "natural" train of modulated signals corresponding to the semidiurnal tides. This span contains an anomalous phase delay between the enveloping curves of the semidiurnal tidal deformations, which has been observed in the earlier experiments and is discussed below in this article. The experimental enveloping curves, as against the theory, show the phase delay 1 day long, which is of regular nature [6]. In the meanwhile, it is seen in the graphs that the time delay closer to the earthquake point changes and reaches approximately 4 days.

Figure 4 offers one more example of abnormality in the amplitude of semidiurnal tidal harmonics in the period of initiation of a regional earthquake focus. Such behavior was recorded a weak before the event of energy class K = 12.6 on 27 Sep 2010. The abnormality is traced in the East–West arm, which conforms with the direction from the seismic station to the earthquake epicenter within the accuracy of 10°.

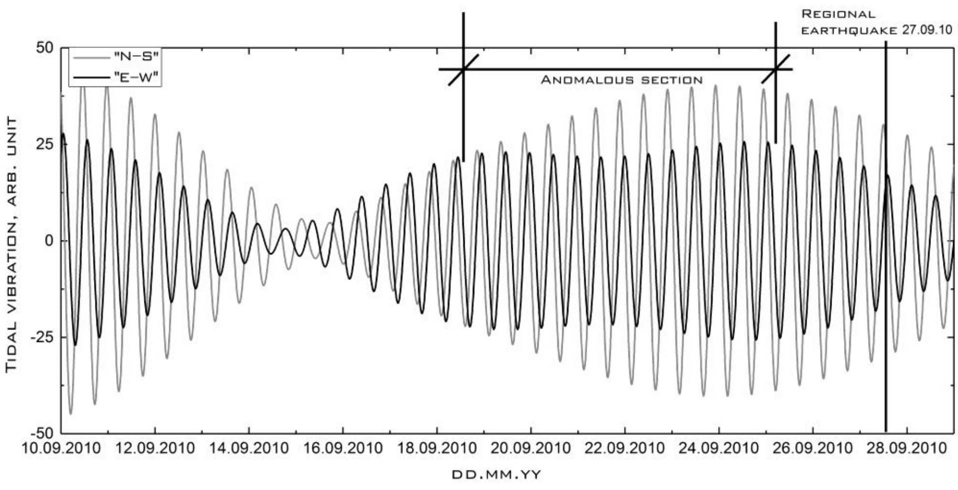

Figure 4. Anomalous behavior of semidiurnal tidal wave amplitude in the East–West arm of the deformograph.

4. Phase differences between enveloping curves of semidiurnal tides for 14 days

Thus, it has been noticed that there is a phase delay of the order of 1 day between envelopes of the semidiurnal tide curves recorded for 14 days. The theoretical curves modeled for various arms of the deformograph coincide, i.e., the theory forecasts none of the phase delays [7]. Figure 5 illustrates the described behavior of ерy envelopes. At the top of the figure, there are theoretical enveloping curves of semidiurnal tides, and at the bottom, there are envelopes of the filtered experimental data. Modeling of the crustal tides was carried out using Etgtab 3.0 program from Eterna 3.0. In this program, the parameters of the Talaya seismic station and the deformographic characteristics were set, e.g., coordinates and altitude of the station, displacement measurement direction (azimuth), measurement start time, sampling rate, etc. In this manner, theoretical data can match up with the experimental recording in each measurement arm of the deformograph. Then, the experimental and theoretical results are subjected to digital band-pass filtration in the wanted range of frequencies. It is worthy of mentioning that in figure 5, for the convenience of visualization, the normed enveloping curves are shown, which entails the loss of information on the amplitude differences between the orthogonal tides, observable on the left-hand side of figure 4.

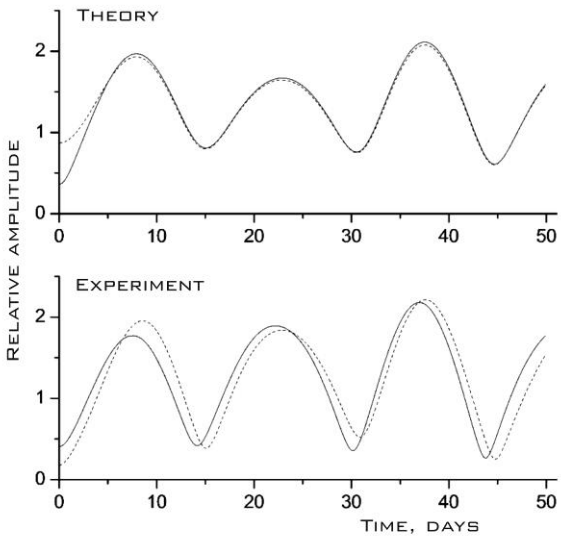

Figure 5. Phase delay between the enveloping semidiurnal tide curves based on the data from the orthogonal arms of the deformagraph (bottom) and no delay in the theoretical data (top).

The detailed study of the delays in the set of data recorded in 14 days proves both presence and value of the delay. Poor accuracy of the estimates is from the noise and perturbations in the recording.

Characteristic delays for the semidiurnal tide are:

- Arm 1 – experiment is delayed by 9–10 h;
- Arm 2 – theory is delayed by 7–9 h.

Characteristic delays for the diurnal tide:

- Arm 1 – experiment is delayed by 10–12 h;
- Arm 2 – theory is delayed by 9–11 h.

The phase delay, unexplained theoretically, should be more investigated as it is a potential sign of large seismic events. The investigations should be based on long-term continuous deformation monitoring using supplementary procedures of observation and data interpretation.

Acknowledgements
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