THE RESULTS OF LONG-TERM REGISTRATION OF MICRO-DEFORMATIONS OF THE EARTH'S CRUST IN THE AREA OF LAKE BAIKAL

Alexander Yu. Rybushkin[1]
Yury N. Fomin[2]
Vladimir Yu. Timofeev[3]
Denis O. Tereshkin[4]
Vladimir M. Semibalamut[5]
Vadim A. Zhmud[6]
Lubomir V. Dimitrov[7]
[1, 2, 3, 4, 5]Siberian Branch of the Federal Research Center unified geophysical service of the Russian Academy of Sciences (SIBGSRAS), Novosibirsk, Russia
[6]Novosibirsk State Technical University, Novosibirsk, Russia
[6]Institute of Laser Physics SB RAS, Novosibirsk, Russia
[6]Novosibirsk State University, Novosibirsk, Russia
[7]Technical University of Sofia, Sofia, Bulgaria

ABSTRACT

Long-term registration of small deformations of the Earth's crust with the subsequent data processing is necessary for solving many actual problems. Such deformations are measured predominantly using unique laser measurer (deformograph). Experimental data allow us to investigate the frequency spectrum of deformations and on the basis of this analysis to draw conclusions about the level of seismic activity in the region. Variations of the tidal parameters allow estimating the parameters of the fractured zone. Measurements of deformations in two orthogonal directions are carried out using an original automated laser measurer for ultra-small movements of the Earth's crust. The advantage of the laser measuring complex created for measurements in the mountain tunnel is that even in the presence of the atmosphere it possesses a high relative sensitivity of the order of 10^{-9}-10^{-10} to small displacements in a wide range of oscillation periods of 10^{0}-10^{7} s. It allows recording of the Earth's own and tidal oscillations, deterministic daily variations of micro deformational oscillations, as well as features of the deformation processes in the Earth's crust that accompany seismicity. This paper presents the results of long-term monitoring of oscillations of the Earth's crust in the area of Lake Baikal, measured in the observatory Talaya in mountain tunnel with a laser meter.

Keywords: *laser deformation measurer, short-term precursors of earthquakes, Baikal region, methods of gallery deformation registrations, modern field of strain rates*

INTRODUCTION

The Siberian Branch of the Federal Research Center unified geophysical service of the Russian Academy of Sciences (SIBGSRAS, Novosibirsk, Russia) has developed and manufactured several variants of laser meters for ultra-small deformations of the Earth's crust in two orthogonal directions [1], [2]. The devices were used in Altai Mountain Region, in Kazakhstan and other regions. It is used for the longest time in the long-term working mode at the Talaya observatory near Lake Baikal. This paper proposes the results of the development and improvement of methods for recording and interpreting minor deformations of the Earth's crust using the mentioned measuring complexes of highly sensitive laser equipment in the Baikal seismic zone. The study of deformation processes is due to the need to fill in the lack of information about the signs of preparing strong earthquakes and, as a result, the lack of reliable methods for their prediction. This deficiency is especially acute in the Baikal seismic zone, where the insufficient technical equipment of the existing geodynamic polygons does not allow achieving sufficiently reliable results for the detection of earthquake precursors. At present, an experimental sample of a two-coordinate strain gauge based on two He-Ne laser emitters has been used successfully for a long time in the gallery in the Talaya Observatory (Southern Baikal). The measuring base of the device is 25 m. With its help, deformation processes are recorded in order to study the geodynamics of the Earth's crust of the Baikal rift zone and the registration of deformation precursors of earthquakes.

LONG-TERM MEASUREMENT RESULTS

The laser deformograph at the Talaya station can be used as a tool to study the natural oscillations of the Earth, seiches of the Baikal Lake, tidal deformations of the Earth and slow deformations in the seismically active Baikal region. Let us consider examples of the use of an laser deformograph installed in the mountain tunnel in the seismic station. The position of the Talaya seismic station is shown in Fig. 1 [3].

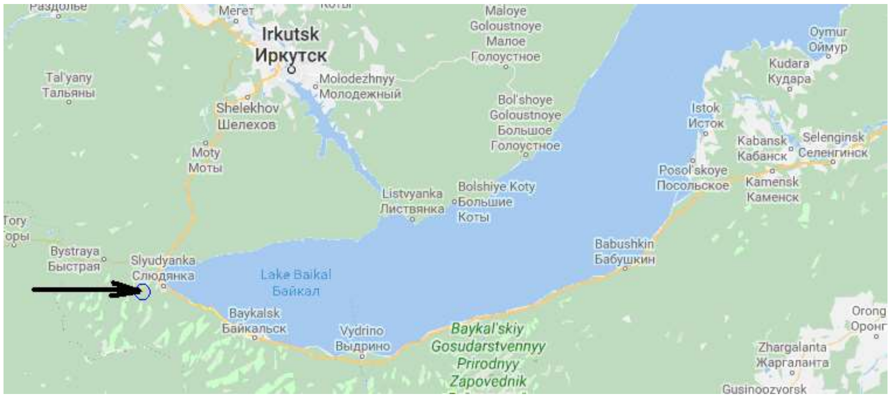

Figure 1: Position of Talaya station near Slyudyanka village near Lake Baikal

THE EARTH'S OWN OSCILLATIONS ACCORDING THE COLLECTED DEFORMATION DATA

The Earth's own oscillations are one of the important areas of geophysical prospecting. Experimentally, the natural oscillations join seismology and gravimetry. Periods of natural oscillations are known from 57 min to 35.5 min.;

25.8 min.; 20 min.; 13.5 min.; 11.8 min.; 8.4 min and less. An example of the spectral analysis of the deformograph recording (Mokh Observatory, Germany) after the Sumatran earthquake (December 26, 2004, M = 9) is given in [4]. Let us turn to the records of the laser deformograph obtained at the Talaya station (Fig. 2) during the period of the catastrophic earthquake in Japan (March 11, 2011, M = 9.1). As usual, we analys the registration records obtained from measurements with a 25-meter laser strain gauge along two orthogonal axes (–24°N, + 66°N) and difference deformation. Fig. 3 shows filtered deformations records for the same period in which the low frequency component is eliminated. Fig. 4 shows the difference signal, which shows the effect of the earthquake that took place on 11.03.2011. Fig. 5 shows the difference signal after filtering it with a high-pass filter, while the entire interval is stretched along the time axis, the entire axis represents the interval of two days. It can be concluded that the indicated oscillations are well distinguished by the used instrumentation; they appear in the difference signal no less clearly than in the signal along the individual arms of the interferometer.

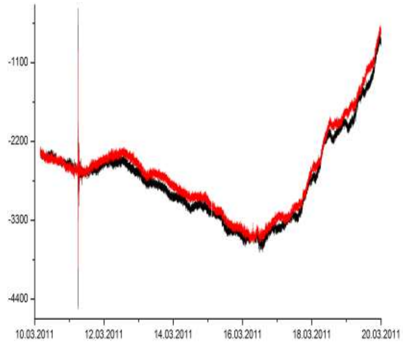

Figure 2: The graph of deformation in two azimuths from March 10 to March 20, 2011, including the date of the earthquake on March 11, 2011 (M = 9.1)

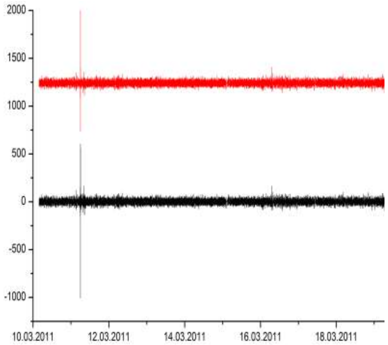

Figure 3: Filtered deformation records for 10 days, including the date of the earthquake on March 11, 2011, in the range of 1 min - 1 hour

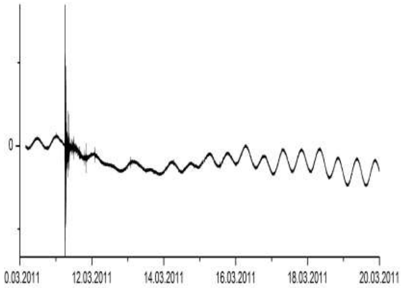

Figure 4: Difference signal, earthquake effect on the 03/11/2011 and tidal variations

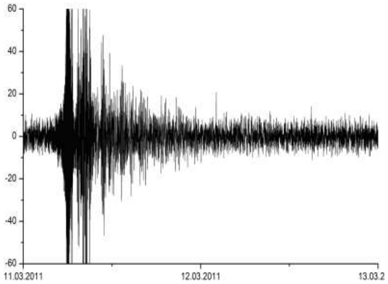

Figure 5: Filtered differential signal (2 days of recording)

VIBRATION SPECTRUM STUDIES

To study the processes it is also advisable to construct the spectra of the obtained oscillations. Fig. 6 shows the spectra at various times after an earthquake. It is possible to note changes in the spectrum for the day following the earthquake. There are separate peaks in the frequency range from 0.0003 Hz to 0.0015 Hz: 0.00029 Hz (which corresponds to period of 57 min.); 0.00047 Hz (35.5 min.); 0.00065 Hz (25.8 min.); 0.00083 Hz (20 min.); 0.00123 Hz (13.5 min.) and 0.00141 Hz (11.8 min.). Fig. 7 shows the spectra of the difference signal. In the spectra, frequencies of torsion and spherical vibrations are distinguished. From experimental data more than 1000 periods of natural oscillations are known.

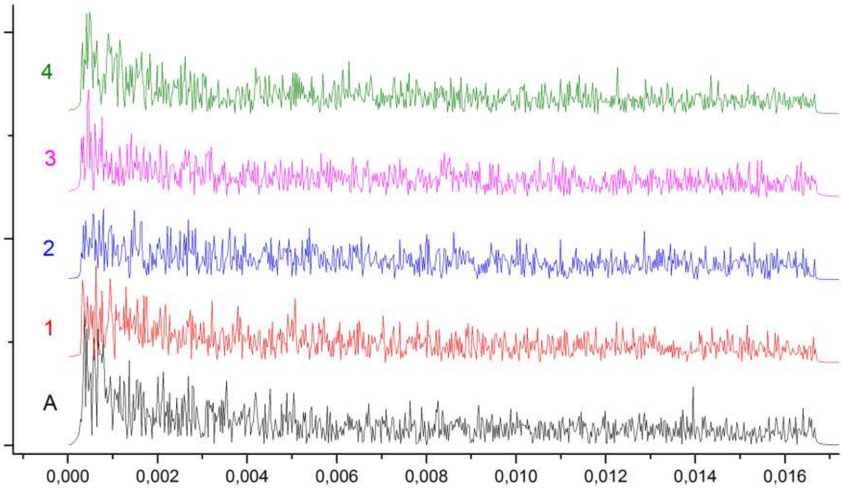

Figure 6: Spectra of the deformation signal in a window 6 hours long: A - immediately after an earthquake; 1 – after 1 day; 2 – after 2 days; 3 – after 3 days; 4 – after 4 days

Since the Earth's core is liquid, and torsion vibrations are transverse vibrations, they are associated only with solid regions of the Earth and are determined by the distribution of the density and shear modulus in the shell (mantle) and crust. It is known that, due to the study of natural oscillations, of two models of the Earth: a) the Gutenberg model with a layer of lowered speeds of seismic waves at depths of 50 km ÷ 250 km and the model; b) Jeffreys model, which does not have such a layer, self-oscillations very strongly favor “preference” Gutenberg models. Spherical vibrations capture the entire Earth, which allows studying the core of the Earth along with the crust and the shell. Different frequency intervals are determined by the properties of different areas of the Earth's interior.

Therefore, natural oscillations allow one to study not only the integral properties of the globe, like tides in the body of the Earth, but also differential ones. As shown, the above laser deformograph can serve as an important part of the instrumental complex for studying the natural oscillations of the Earth.

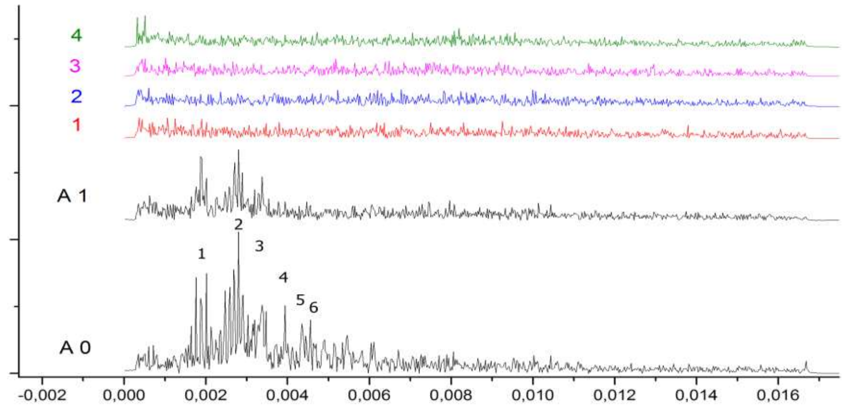

Figure 7: Spectra for the difference: A0 - immediately after an earthquake; A1 - after 3 hours. The approximate value of the harmonics: F1 = 0.00184435421 Hz, F2 = 0.00272346129 Hz, F3 = 0.00335752109 Hz, F4 = 0.00390581435 Hz, F5 = 0.0042917638 Hz, F6 = 0.00456437888 Hz (corresponds to periods in minutes: 9.0365; 6.11966; 4.96397; 4.26714; 3.88340 and 3.65146)

TIDES AND SEICHES OF BAIKAL LAKE

Consider the natural oscillations of Baikal Lake, i.e. seiches. They can be observed by measuring the level of the waters of Baikal or the displacement of its ice cover (in winter). In the GPS measurements in 2007, there were variations in vertical displacements of the ice cover with periods ranging from 4 hours to one day (see Fig. 8). Consider these vibrations, which, loading the Earth's surface (the bottom of Baikal Lake), cause deformations of the Earth's crust, which can then be recorded by laser deformograph in the tunnel of the Talaya seismic station located 7 km from the lake (see Fig. 1).

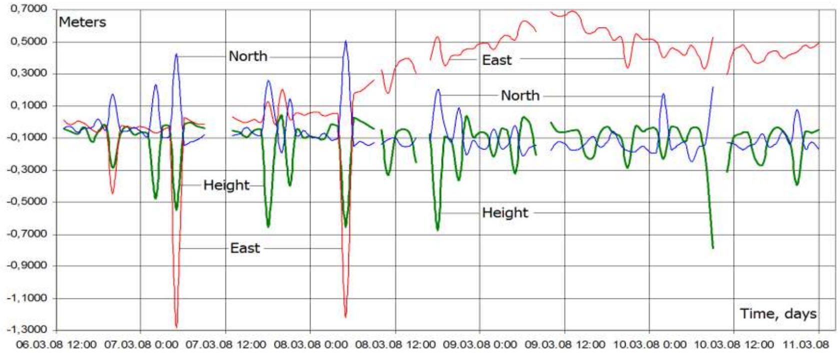

Figure 8: The results of GPS measurements in height, in azimuth to the East and in the azimuth to the North. Offsets of the "Balok" ice point relative to the "Baza" coastal point, at 3 km from it. Time is from 12h 03/06/2008 to 00h 08/03/2008. The picture shows a seiche period of 4 ÷ 5 hours

These variations are related to the tides and seiches of the lake. Let turn to the nature of these effects. The tides of Baikal Lake were considered in the works of the period from 1920 to 1960, and for similar in size and location of Tanganyika Lake in Africa; a detailed analysis is given in [5]. It is known that at the Tankhoi and Peschanaya points tidal semi-diurnal waves (M2) were observed with amplitude of 5-6 mm with a 20% error. For the Baikal Lake analogue, Tanganyika Lake in Africa (the lake is 638 km long and the average depth is 800 m), observations were made at Albertville, where the lake is 75 km wide. The median position of the item allows you to register a unimodal 4 hour seiche, a bimodal 2 hour seiche and 40 minute seiche. Taking into account the short period of natural oscillations of lakes, the static theory of tides can be used to analyze tides with a period of 12 hours or more. Normal gravimetric and oblique factors were obtained for the Baikal region and the tidal deformation model was chosen [6], [7], [8], [9]. Using the tidal analysis method HICUM to estimate the amplitudes of the main tidal waves at Listvyanka, we obtain values: from 7.8 ÷ 7.9 mm (M_2) to 20.9 mm (M_f) and from 4.3 ÷ 4.6 mm (O1) to 6.38 ÷ 6.9 mm (K_1). Full tide reaches several centimeters. The long-period tide is complicated by seasonal variations in lake level. Using the static tide theory, we analyze the periodic variations using the ETERNA method [10]. Table 1 presents the results of the analysis when using the version of the slopes in the azimuth of East. However, the phase shift for the M2 wave and other main waves turns out to be great; therefore, a search with a minimum phase shift was found, it turned out that it is better to use the azimuth “70°N” (see Table 2).

Table 1: Tidal analysis of a series of 282 days (April 28, 2007 - March 5, 2008), ETERNA program (1) Verification, azimuth angle 90°

Wave	Amplitude [*mm*]	SNR	Amplitude factor	Error	Phase shift [°]	Error [°]
O1	3.442	26.6	0.672	0.025	13.05	1.44
P1S1K1	4.532	35.9	0.629	0.017	19.34	0.99
N2	1.238	8.6	0.662	0.077	9.42	4.42
M2	7.962	51.7	0.815	0.015	13.79	0.90
S2K2	3.562	24.0	0.784	0.032	26.02	1.87

Table 2: Tidal analysis of a series of 282 days (April 28, 2007 — March 5, 2008), ETERNA program (1) Verification, azimuth angle is 70°

Wave	Amplitude [*mm*]	SNR	Amplitude factor	Error	Phase shift [°]	Error [°]
O1	3.441	26.6	0.710	0.026	6.83	1.53
P1S1K1	4.533	35.9	0.665	0.018	13.16	1.05
N2	1.235	8.6	0.675	0.078	-6.20	4.50
M2	7.964	51.7	0.834	0.016	-2.17	0.92
S2K2	3.562	24.0	0.802	0.033	10.05	1.95

We use this model of tilt in azimuth of 70°N for the analysis of Baikal tides. The relation between the vertical displacement Δr and the inclination of the surface ε [11] is known:

$$\Delta r = (L/2)\cdot\sin\varepsilon\,,\quad \varepsilon(\text{rad}) = 2\Delta r / L\,.$$

Here L is the width of the lake in a given azimuth. For wave M_2, we observe a vertical displacement of 7.964 mm. The corresponding vertical slope is:

$$\varepsilon = \mathrm{A}_{\text{th}}\cdot\gamma_{\text{th}}\,.$$

The astronomical amplitude A_{th} (9.544 ms) for a solid Earth is modulated by the elastic response of the Earth according to the ratio for the amplitude factor $\gamma_{\text{th}} = 1 + \mathrm{k} - \mathrm{h} = 0.69125$. Its theoretical value, according to the results obtained for Talaya station, is $\gamma_{NS}= 0.704$ and $\gamma_{EW} = 0.710$ [10]. Therefore, we assume ε(ms) = 6.597 and ε(rad) = 31.98 nrad. Substituting these values in the ratio:

$$L = 2\Delta r / \varepsilon\ \text{(rad)}.$$

The calculation gives L = 498 km. The same calculations give for L = 412 km (S_2), L = 420 km (O_1) and L = 440 km (K_1) waves. These calculations are made similarly to the analysis for Tanganyika Lake, where assumptions about zeroing tidal amplitudes in the center of the lake are made. In our case, for Baikal Lake, for the length L it is more correct to choose the ratio:

$$L = \Delta r / \varepsilon\ \text{(rad)}.$$

This gives a value of L ranging from 206 km to 249 km, which corresponds to the size of the southern depression of the lake (see Fig. 9).

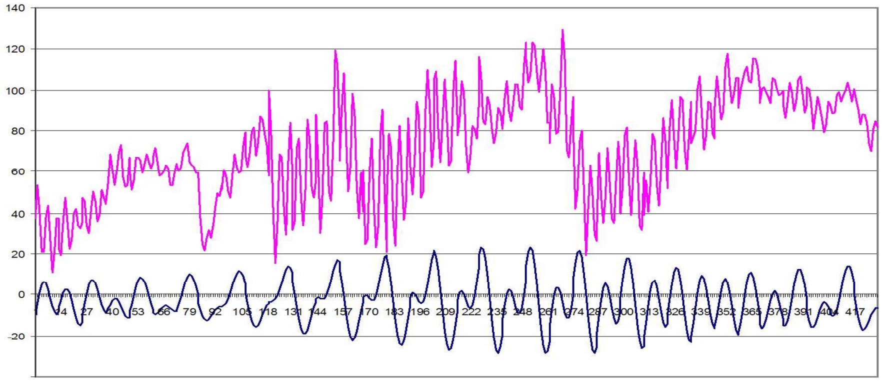

Figure 9*: Variations of the level of Baikal Lake with the exception of the tidal effect – seiches (row 1, in mm) and the theoretical tidal curve. Generate seiches at high tide. Double amplitude of seiches reaches 60 mm at Listvyanka*

The two-week wave Mf has an amplitude higher than the theoretical one, which requires the further development of the dynamic tide theory at Baikal. Two-week modulation of the tide, along with earthquakes and abrupt changes in atmospheric pressure, is one of the causes of standing waves – seiches on Baikal (see Fig. 11). Excluding tidal variations from observations of the level and making spectral analysis, we obtain seiches periods: 4 h 33 m, 2 h 33 m, 1 h 28 m and 1 h 06 m for the item Listvyanka. Nodal lines of seiches are located at a distance of 280 km, 130 km, 360 km and 540 km, respectively, from the southern part of the lake (Kultuk settlement).

The theoretical periods of seiches are related by the equation:

$$T_n = 2l / (n\sqrt{gH}).$$

Here l is the length of the lake, H is its average depth, g = 9.8 m / s2 and n is mode. For the first seiche mode with a period of 4.6 hours, we obtain the value of an average depth of 630 m. The amplitude of the seiches has seasonal changes. The first mode of seiche is well manifested in the records of the lake level at the Listvyanka station and in the data of ice measurements of displacements. Simulation of tidal and seiche effects of Baikal Lake is important for the development of monitoring measurements in the Baikal region. Periodic load at the bottom of the lake at level 1 KPa manifests itself in various types of high-precision geophysical measurements. We now turn to the results of observations in this frequency range by a laser deformograph at the Talaya station. The spectral analysis of the materials was performed using a filter whose amplitude-frequency characteristic is shown in Fig. 10. Among the obtained frequencies, besides those noted in Listvyanka (periods of 4.55 hours; 2.55 hours; 1.47 hours and 1.1 hours), oscillations with a period of 3.4 hours (205.5 minutes) are distinguished. The summer frequency spectrum is richer, which may be due to the filtration properties of the ice layer on Baikal Lake. The deformation spectra for the winter and summer periods of observations are analyzed, a typical example of which is shown in Fig. 11.

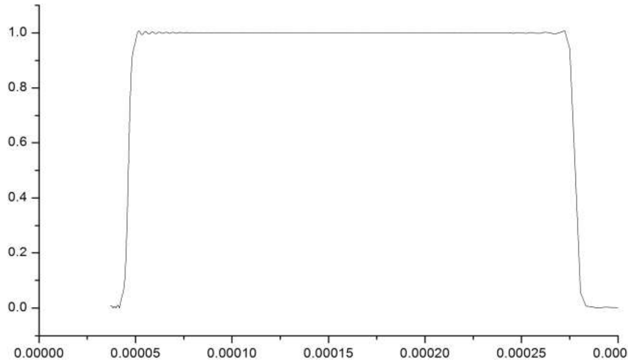

Figure 10*: Frequency characteristics of the filter*

In the future, fluctuations from the seiche period of Lake Baikal can be used to build a dynamic model of the lake level, and the presence of these periods in deformograms should be taken into account in further analysis and interpretation.

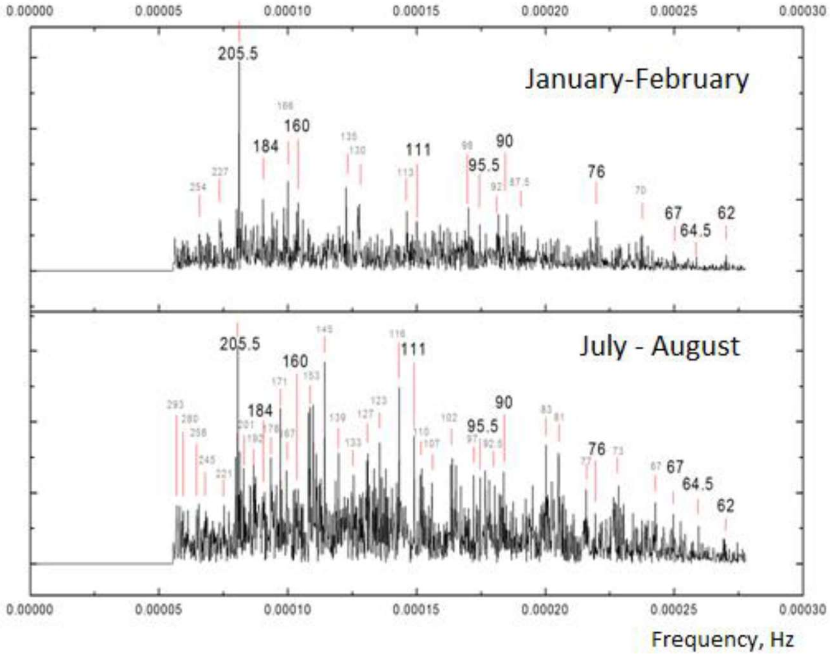

__Figure 11__: Spectra for winter and summer periods of observations

TIDAL DEFORMATIONS AND VARIATIONS OF TIDAL PARAMETERS DURING TIME

Tidal deformations of the Earth cover the entire planet from its center to the surface. They have an amplitude of 10^{-8} units, and the tidal force is accurately calculated [4]. Experimental selection of tidal models for southern Baikal was carried out using data obtained using digital tidal gravimeters and laser deformographs [5], [6]. Reflection of the effects of the cavity, local features of the Earth's crust and in tidal deformations for the Talaya station reach 10% in amplitude and 9° in the phase shift [9]. The greatest interest in the analysis of tidal oscillations is the 12-hour harmonic (wave M2), since the information contained in this signal is less noisy, while the 24-hour tidal harmonic is usually distorted by daily variations of meteorological parameters. The results of the tidal analysis were performed using the ETERNA.3.0 program according to the annual data of difference deformations. Fig. 12 and 13 show variations of the amplitude factor and phase shift (difference from the normal state + 65.4°) for the period from 1995 to 2015. Usually, graphs were based on quarterly data. In the last years, due to the instability of the power supply at the seismic stations, the average annual data was used. As can be noted from the results of the analysis, the perennial variations of the parameters lie within a few percent. Variations in the phase shift after the Kultuk earthquake (M = 6.3, 25 km from Talaya station, 08.27.2008) smoothed out (see Fig. 13), which apparently reflects the state of the geological environment of the area. In epochs of strong earthquakes, variations in tidal parameters reach 3–4% in amplitude and 1–3° in the phase shift. Anomalies can be caused by changes in hydrodynamic conditions in the zone of a deep fault (1-3 km from the observation point) and deformation of the Earth's crust in the era of a strong earthquake.

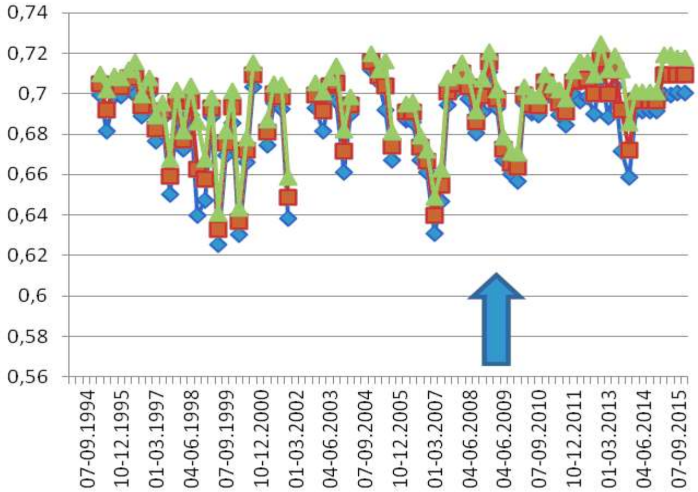

Figure 12: *Amplitude factor (1990–2015)*

Figure 13: *Phase shift (1990 – 2015), the normal value is 65.4°*

LONG-TERM PERENNIAL VARIATIONS

Periodic variations of perennial changes in deformations reflect variations in local deformation of near-fault zones (in our case, the Main Sayan Fault, located a few kilometers north of the station). Long-term changes of deformations show the prevailing direction of deformation and reflect the development of the seismic process in the region. The local level for deformations was investigated according to the data obtained in the 90-meter tunnel of the Talaya seismic station. Here at the bases of 1 m – 25 m the annual strain rate reaches a year. This characteristic, apparently, is local (in contrast to the data of space geodesy). In the past two years, due to the instability of the power supply at the seismic station, the data on the course of deformation during the year is unreliable; therefore, only information from previous years was used in the analysis. Over long time series (1985–2013), the deformation is cyclical in nature (periods from 3 to 18 years), the average strain rate becomes comparable with the definitions on large bases. In moments of strong regional earthquakes, local deformation reflects the regional character (co-seismic changes up to 3·10-6 per year). Measurements in two orthogonal azimuths allow one to obtain the values of the first invariant of the strain tensor – the bulk strain and to analyze its behavior in time.

To exclude the seasonal component, the total results for the annual period are analyzed. Fig. 14 shows changes in the rate of accumulation of volumetric strain in time; the arrows also show the moments of Busingolsky (12.27.1991, M = 6.5-7.0), Zunmurinsky (June 29, 1995, M = 5.6-5.8), South Baikal (25.02.1999, M = 5.9-6.1) and Kultuk earthquakes (August 27, 2008, M = 6.3). Starting from the period of 1994–1996, the Main Sayan fault is blocked by GPS data, during this period according to the laser deformograph, until 2001 there is a slight variation in the volume strain, and then from 2001 until the Kultuk earthquake, an accumulation of tensile strain occurs. Obtained with strong earthquakes (M > 6) co-seismic changes of deformations and displacements allow testing dislocation models of earthquakes, which gives additional information to determine the parameters of strong earthquakes: the position of the epicenter, hypocenter, depth, position of the nodal plane and the direction of movement in the earthquake source. An analysis of the areas of anomalous displacements and deformations obtained before the event showed that their sizes correspond to areas of significant co-seismic effects. The accumulation of deformation stretching continued after the 2008 Kultuk earthquake. In recent years, it has been replaced by compression (4·10-7 per year).

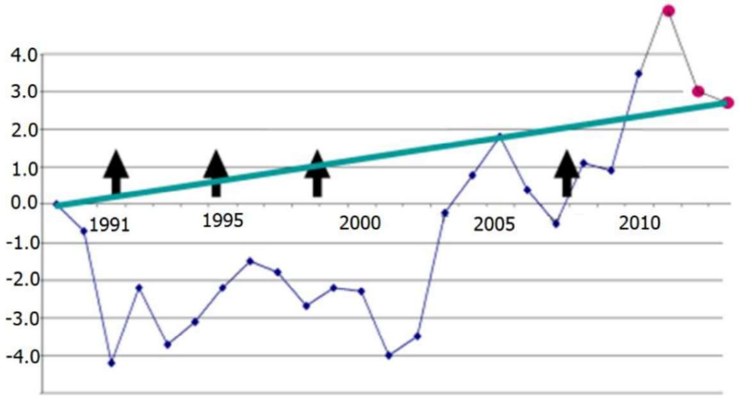

***Figure 14**: The change in volume strain (×106) for the period from 1989 to 2013 (areal deformation is equal to the sum of changes in two orthogonal azimuths; volumetric deformation is equal to areal one multiplied to 2/3); the slope of the middle line is 10-7 per year.*

CONCLUSION

The paper reports about observations of conduct of the deformation processes in the tunnel of the Talaya Observatory using a He-Ne laser measuring device. The current on-line processing of the incoming data of deformographic observations has been completed.

Analysis of laser deformograph records obtained after a catastrophic earthquake in Japan (March 11, 2011, M = 9.1), allowed us to determine the values of the natural oscillation periods of the Earth. In the spectra, frequencies of torsion and spherical oscillations with periods of 57 min are distinguished; 35.5 min.; 25.8 min.; 20 min.; 13.5 min.; 11.8 min.; 9.0 min.; 6.1 min; 4.9 min; 4.2 min.; 3.8 min. and 3.6 min. Different frequency intervals are determined by the properties of different areas of the Earth's interior. It is shown that a laser deformograph can serve as an important part of the instrumental complex for studying the natural oscillations of the Earth. The natural oscillations of Baikal Lake (seiches) are investigated. Using the available digital records of deformations, the spectra for the winter and summer periods of observations were analyzed. The summer frequency spectrum is richer, which may be due to the filtration properties of the ice layer on Lake Baikal in winter. Further, oscillations with a period of seiches of Lake Baikal can be used to build a dynamic model of the lake level, and one should also take into account the presence of these periods in deformograms with further analysis and interpretation.

REFERENCES

[1] Zhmud V.A., Semibalamut V.M., Dimitrov L.V., Taichenachev A.V.. The Phase Locking System for the Frequency Locking of Lasers for Geoinformatics. 18th International Multidisciplinary Scientific GeoConference “Informatics, Geoinformatics and remote sensing” SGEM 2018. Conference proceedings. Vol.18. Issue 2.2. Informatics, Geoinformatics. Albena, Bulgaria. P. 491–498.

[2] Zhmud V., Tereshkin D. Modification of software for the control of laser measurer of super small deformations. 2013. 8th International Forum on Strategic Technology 2013, IFOST 2013 - Proceedings P. 260–264.

[3] https://www.google.com/maps/ .

[4] Jahr T, Kroner C, Lippmann A. Strainmeters at Moxa observatory. Journal of Geodynamics. Germany 2006. V.41. P.205–212.

[5] Melchior P., 1983, The tides of the planet Earth, 2nd ed. Pergamon Press, Oxford, 641 p.

[6] Dehant V, Defraigne P, Wahr J. Tides for a convective Earth. J. Geoph. Res. 1999. V.104, B1, P. 1035-1058.

[7] Ducarme B., Venedikov A. P., Arnoso J., Vieira R. Determination of the long period tidal waves in the GGP superconducting gravity data. J. of Geodynamics. 2004. V.38, P. 307-324.

[8] Ducarme B., Vandercoilden L., Venedikov A.P. The analysis of LP waves and polar motion effects by ETERNA and VAV methods. Bulletin Inf. Marées Terrestres. 2006. V.141. P. 11201-11210.

[9] Ducarme B., Timofeev V.Yu., Everaerts M., Gornov P.Y., Parovishnii V.A., Ruymbeke M. van. A Trans-Siberian Tidal Gravity Profile (TSP) for the validation of the ocean tides loading corrections. Journal of Geodynamics. 2008. V. 45. N.2-3. P.73-82.

[10] Wenzel H.G. The nanogal software: earth tide data processing package ETERNA 3.30. Bull. Inf. Maréees Terrestres. 1996, V.124. P. 9425-9439.

[11] Timofeev V. Y., Ardyukov D. G., Gribanova E. I., van Ruymbeke M., Ducarme B., Tidal and long-period variations observed with tiltmeters, extensometers and well-sensor (Baikal rift, Talaya station). Bull. Inf. Marées Terrestres, 2009. 135 p.