Bull. Nov. Comp. Center, Math. Model. in Geoph., 11 (2006), 1–14

Active vibromonitoring research: experimental systems and results

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Abstract. Methods of active geophysical monitoring with the use of powerful seismic vibrators play an important role in the investigation of changes in the stressed-deformed state of a medium in seismic prone zones for problems of the seismic hazard prediction. During the last three decades, this scientific field has been actively developed at institutes of Siberian Branch of the Russian Academy of Sciences. In this period, experimental systems for the active monitoring of a medium have been made up. They include powerful (vibrational) sources with a vibrational force of 100 tons in the frequency range from 5 to 15 Hz, computer control systems, mobile specialized complexes for the precise recording of vibrational seismic signals, such as VIRS-M, VIRS-K, and ROSA, and computerized data processing systems [1–3].

A method for the active monitoring of a medium with the use of wide band sweep signals and narrow band harmonic signals radiated by seismic vibrators has been developed. In order to determine the sensitivity of the active monitoring system, some experiments to detect the influence of the Earth's crust tidal deformations (of order 10^{-7}) on seismic wave velocities have been performed. A 100-ton seismic vibrator and recording systems were located at a distance of 356 km. The radiation sessions of harmonic and sweep signals were repeated every three hours during four days. This made it possible to construct time series of variations of the signal amplitudes and phases and wave arrival times. Both 12-hour and 24-hour periodicities correlated with the Earth's tides were detected in the spectrum of variations of the recorded signals. The experiment has shown that the active monitoring system makes it possible to detect relative variations of the seismic wave velocities of order 10^{-5}–10^{-6} in an area of 300–400 km around the source. This allows direct monitoring of the state of stresses in an area of 100 thousand km^2 to detect regions and phases of the critical stress as an earthquake precursor.

In recent years, the active monitoring of lake Baikal region has been started. It uses vibroseismic interferometry method, based on the seismic sounding of the region by powerful seismic vibrators with a long-time radiation of narrow band harmonic signals. Changes in the stressed-deformed state are determined through variations of the amplitude-phase characteristics of stationary wave fields, which are excited in the medium due to a long-time radiation of harmonic signals of constant frequency from the vibrator. The method of vibroseismic interferometry has a high sensitivity to the time changes of the parameters of the medium in the case of large-scale observations. A peculiarity of the experiments in Baikal region is the simultaneous use of data from regional seismic stations and from mobile recording complexes.

Introduction

In 1996–1997, the Institute of Computational Mathematics and Mathematical Geophysics of the Siberian Branch of the Russian Academy of Sciences (ICM&MG SB RAS) conducted experiments with the use of low-frequency vibrosources and signals recording at distances of 300–400 km. These experiments were aimed at detection of small variations of time-space characteristics of seismic wave fields and their connection with the deformation processes caused by the Earth's tides.

It is known that semidiurnal and daily tides with periods of 12 and 24 hours occur in the solid Earth. The tidal gravitational influence on the Earth's crust has a number of properties important for seismic monitoring. It is a global phenomenon, which can be observed at any point of the Earth. Its periodical changes may be predicted with a very high accuracy, and may serve as a natural standard of the deformation forces in the lithosphere. The use of this standard for studying variations of the stressed-deformed state of the Earth's crust and the upper mantle by seismic methods demands high metrological characteristics of systems for deep seismic sounding.

A variety of experimental works deal with investigations of the influence of tidal deformations of the Earth's crust on the changes of the seismic wave velocities. The main question in this research was: whether the tidal deformations of order 10^{-7}–10^{-8} result in much bigger relative variations of seismic wave velocities?

The main obstacle in these experiments was a limited accuracy of measurements. When the arrival time variations of P- and S- waves of earthquakes were analyzed, the greatest values of variations of the seismic waves velocities (10^{-2}) correlated with a phase of the Earth's tides were obtained [4]. In investigations with the use of explosions and earthquakes, variations of velocities comparable with the accuracy of measurements of 10^{-3}–10^{-4} were detected [5, 6]. Experiments executed with the use of the vibrator had the same accuracy and were carried out at an offset of 10 km [7, 8]. In Scandinavia, an experiment on recording the harmonic radiation of a hydropower station by the NORSAR at distances of 5–14 km was carried out [9]. In this experiment, relative changes of velocities of seismic waves of 10^{-3} were detected. An experiment on the detection of variations of the first arrivals times on vibrograms with a low-frequency vibrator and an offset of 125 km was performed [10]. It did not show the presence of velocity variations exceeding 10^{-4}.

In all experiments mentioned, if variations of seismic velocities were observed, they had values comparable with the accuracy of measurements. A reliable conclusion on their connection with tidal deformations of the Earth's crust was not possible. In particular, some dependence was revealed: if characteristics of a source are not precisely known, bigger variations of seismic wave velocities, connected with tidal processes, could be obtained in experiments. The results of the experiments have shown that for the detection of variations of seismic waves caused by the Earth's tides, big offsets (several hundreds km) and highly-stable sources are necessary for increasing the accuracy of measurements.

1. The active monitoring technique

The technique of vibroseismic interferometry was used in the experiments conducted in the ICM&MG SB RAS. It is based on radiation and recording of harmonic signals from powerful vibrators. Due to a high stability of harmonic signals radiated by vibrators, their parameters are determined with high accuracy at a recording point. In the spectrum of harmonic signals, the signal/noise ratio for the amplitude makes up 50–100 for distances of 300–400 km for sounding sessions with duration of 20 min. Thus, the amplitudes of harmonic signals are determined with an accuracy of 1–2 %. The accuracy of phase determination is 0.5–1 degree. It enables the detection of integrated changes of the wave field associated with changes of the wave arrival times several milliseconds. It may be effectively used for revealing small variations of characteristics of a medium in geodynamic processes [11, 12].

2. Active vibromonitoring experiments

The periodic radiation of seismic signals of constant frequency was used to detect the time variations of parameters of vibroseismic fields in the experiments of 1996–1997. Excitation of harmonic signals in a frequency range of 6–8 Hz with intervals of 1 and 3 hours during three-four days was realized by the 100-ton vibrator CV-100 located at the Bystrovka test site. Recording the signals was made at distances of 430 km (seismic station Ust-Kan, Republic of Gorny Altai) and 356 km (Savushky, Altai). The scheme of the experiment at a distance of 356 km is presented in Figure 1.

The technique of the experiments provided the simultaneous recording of radiated signals near the vibrator and at remote points with a uniform time synchronization. On the Bystrovka test site, a recording system of radiated signals included a three-component seismometer installed at 30 m distance from the vibrator and recorded the components X, Y, Z of the radiated wave field.

In the first experiments of 1996 on the territory of seismic station Ust-Kan, vibroseismic signals were recorded by a six-channel system CROSS-PC with two three-component short period seismometers SK-1P installed on a rock. Time synchronization of systems of radiation and recording was realized by the GPS. Harmonic signals of the vibrator with a frequency of 6.75 Hz were used. They had a maximal signal/noise ratio at a recording

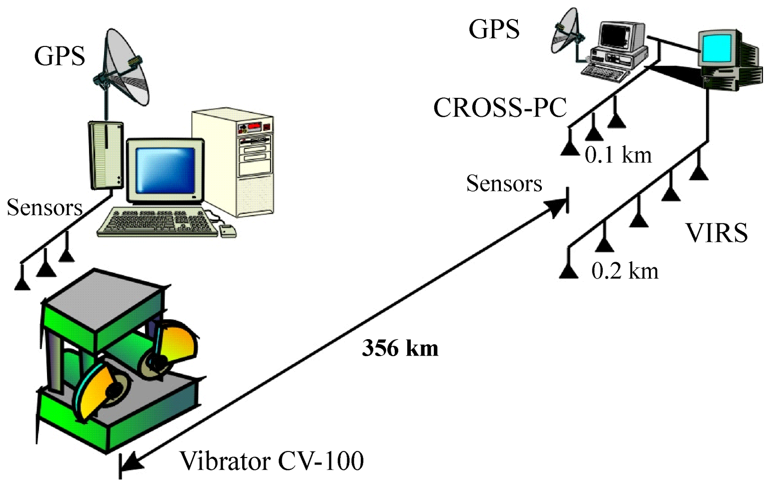

Figure 1. A scheme of the monitoring experiment

point. Periodically repeating radiation sessions were carried out to detect daily variations of the vibrosignals parameters. Three series of periodic nocturnal sounding of a medium on September 28–30, October 5–7, and October 14–16, in phase of two syzygial tides and one neap tide were made. The duration of radiation of harmonic signals in each session was 25 minutes (1500 s). Nine sounding sessions were carried out each night. They followed one by one with a period of 1 hour, from 22 h 30 m up to 6 h 30 m of local time. The choice of this schedule was caused by a low level of microseismic noise at night. Six time series (for X, Y, Z components) with 27 points were obtained for all series of sounding. The reading points were non-uniformly distributed in time with only nine points at night.

In experiments of 1997, at a distance of 356 km, two recording systems were used. The recording complex VIRS had a 15-channel seismic array, which includes five three-component seismic sensors SK-1P. The system CROSS-PC had 3 three-component seismic sensors. Harmonic signals of two frequencies (6.3 Hz and 7.0 Hz) were radiated with duration of 25 minutes each. The experiment lasted four days. Sessions of radiation were repeated every three hours without interruption. Thus, uniform time series with 32 points for each of the 15 components of sensors were obtained. Synchronization of signals of radiation and recording was carried out using the GPS before each session.

Processing of the recording results was based on the spectral analysis of a vibrational signal at the noise background. The 1200-s part of the record, 300 s after the beginning, was used for the analysis. It allowed us to use an established harmonic signal for the processing and to exclude the period of the wave field formation, connected with the arrivals of various waves to

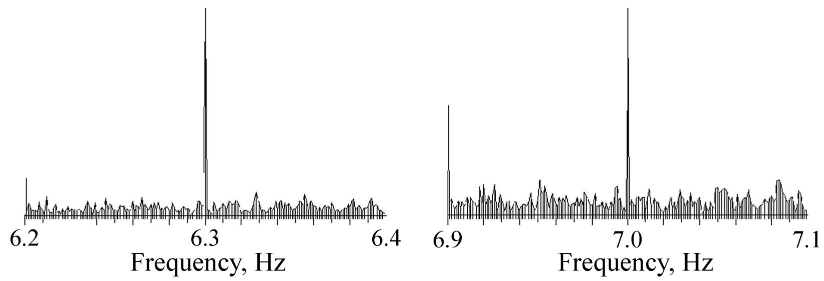

Figure 2. Spectra of harmonic signals with frequencies of 6.3 Hz and 7.0 Hz. Savushky, Altai, distance of 356 km

the recording point. The amplitude and phase of the spectral components of the harmonic signal in a frequency range of 0.0008 Hz were measured as parameters of the signal. The amplitude of the spectral line of a signal is 20–40 times greater than the average spectrum level of noise for the session duration of 1000–1500 s. In Figure 2, the spectra of harmonic signals of the vibrator with a frequency of 6.3 Hz and 7.0 Hz are presented.

For the radiated signal of the vibrator recorded at the Bystrovka test site, the level of signal exceeded the noise level by a factor of 1000. Therefore, parameters of the radiated signal (amplitude and phase) were determined with an error of 0.1 % for the amplitude and 0.1 degree for the phase.

The dispersion of estimates of the parameters of narrow band signals in the method of the vibroseismic sounding was obtained from the power spectral density (PSD) of noise in a narrow band of frequencies in the vicinity of the spectral line of the recorded signal [10, 11]. To estimate the PSD, a frequency band of 0.1 Hz close to that of the radiated signal was used. It included 100–150 spectral lines and gave a representative sample to estimate statistical characteristics of noise. The PSD of noise was estimated separately for each session. It improved the reliability of estimates for the natural nonstationary seismic noise. It was determined that a usual error of estimation of the signal amplitude in the experiments was about 3–5 % for the signal component with a maximal amplitude, and the error of the phase was 1.5–2.5 degrees at the current noise level at recording points.

As a result of the experiments, the time series of amplitudes and phases of the harmonic signal for each component of the three-component seismometers were obtained. The components with a maximal signal/noise ratio were chosen for further analysis. Thus, for a frequency of 7.0 Hz, components $X4$, $Y3$, $Y4$, $Y5$, $Z3$, and for a frequency of 6.3 Hz – components $X3$, $X4$, $Y4$, $Y5$, $Z4$, $Z5$ were chosen.

The time series of vibrosignal phases for further analysis were prepared several stages. Time-synchronization of recording systems with the GPS was carried out several times during the experiment. Therefore it was required to take into account exact times of the beginning of the records files when determining the phases of signals. Similar time series were constructed for the amplitudes of signals with the same components. The preparation of series of amplitudes is somewhat easier than that of series of phases since it is not connected with exact times of recording. When detecting the spectral lines amplitudes with various components, the amplification factor of the recording complex and the vibrator force were taken into account.

The time series of phases and amplitudes with the components X, Y, Z for frequencies of 6.3 Hz and 7.0 Hz are given in Figures 3 and 4.

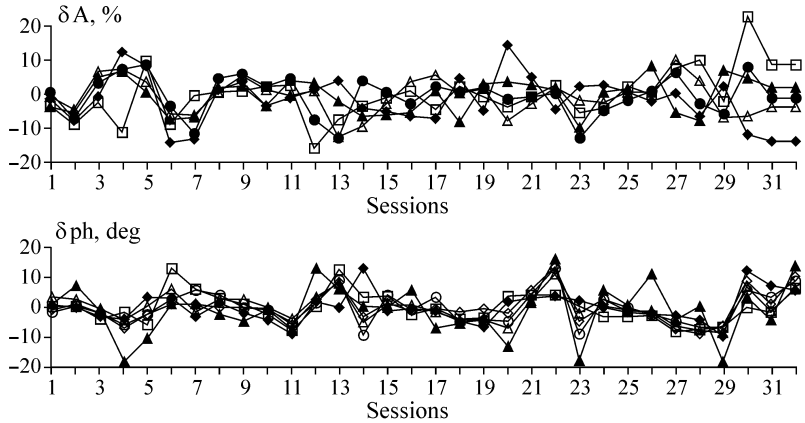

Figure 3. Time series of variations of signal amplitudes and phases. Frequency 6.3 Hz. Distance 356 km

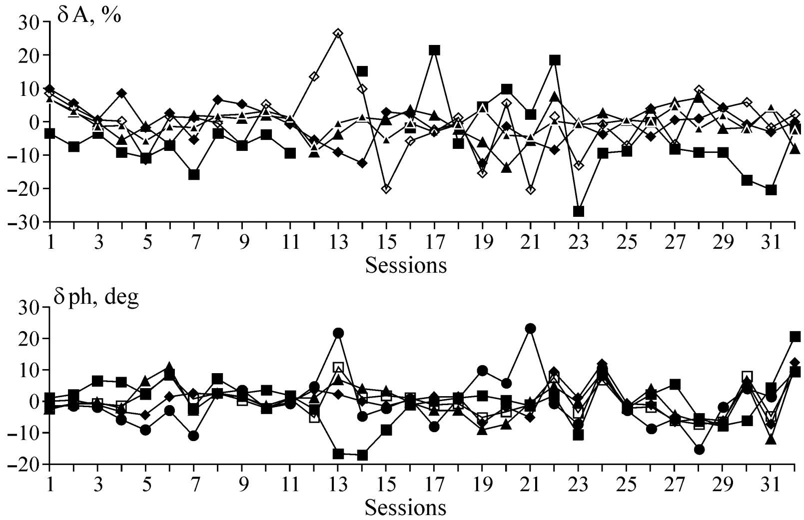

Figure 4. Time series of variations of signal amplitudes and phases. Frequency 7.0 Hz. Distance 356 km

An analysis of the time series of amplitudes and phases of signals for finding latent periodicity was made to determine the relation between the variations of amplitudes and phases of signals and the Earth's tides. The algorithm of Fourier transform for the time series with a non-uniform distribution based on approximation by periodic functions using the least squares method was used to process the results of the experiments at a distance of 430 km. The spectrum component amplitude was determined from functional minimization.

The spectral components for all the time series of amplitudes and phases were determined in an interval from 6 h to 30 h. After that, the spectrum of each time series was normalized to a maximum. The normalized spectra were averaged, and the spectrum of the time parameters averaged over all time series of vibrosignals was obtained.

$$S(T) = \frac{1}{M} \sum_{i=1}^{M} \frac{S_{\varphi_i}(T)}{\max\limits_{T} S_{\varphi_i}(T)}; \qquad (1)$$

where $S(T)$ is a spectrum of variations of parameters averaged over the time series of vibrosignals, i is the number of time series, M is the total number of the time series of phases and amplitudes, T is a period, $S_{\varphi_i}(T)$ is an amplitude in the time variations spectrum.

An average spectrum of variations of the parameters of vibrosignals is presented in Figure 5. There are maxima of the spectrum with periods of 12 and 24 hours. The amplitudes of latent periodicity in the time series of the parameters of signals were estimated using the calculated spectra. They have shown that 24-hour and 12-hour periodicities of variations of the amplitudes of signals is 2–4 %, and an appropriate value of variations of phases is 1–2 degrees. It is necessary to note that the accuracy of these estimates is higher than that of an individual estimate in the measurement of amplitude and phase in one session. For the estimation of one value, information from an ensemble of six time series of variations with 27 points per each series is used. Therefore it is possible to assume that the estimate dispersion of amplitudes approximately decreases by by a factor 5–10. It may reduce the error of determination of amplitudes to 0.5–1 % and to 0.2–0.5 degrees for phases.

Figure 5 shows a spectrum of tidal acceleration, obtained from gravitational measurements. There are maxima with periods of 12 h and 24 h corresponding to the semidiurnal and the daily periods for the spectrum of tidal acceleration.

In spite of the fact that time series with non-uniform points give secondary maxima in the spectrum, as is clear from Figure 5, the experiments of 1996 at a distance of 430 km for the first time have shown the presence of the daily and the semidiurnal periodicity in the time variations of param-

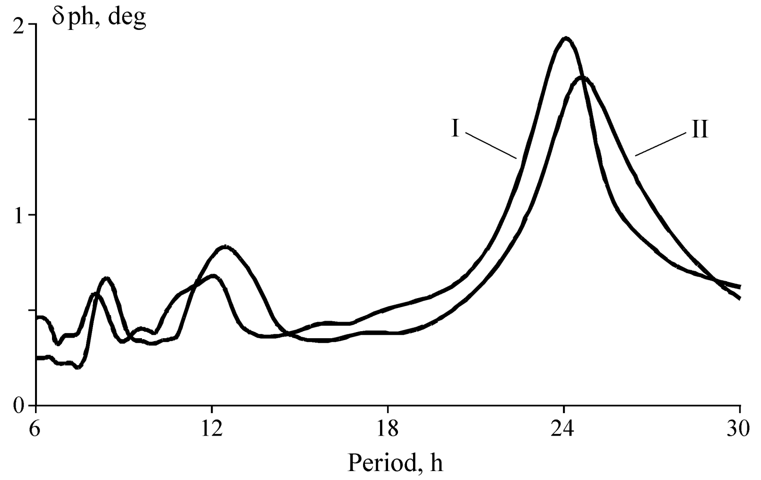

Figure 5. The average spectra of variations of vibrosignal parameters (I) and tidal variations of gravity (II). Vibrator CV-100, frequency 6.75 Hz, distance 430 km

eters of vibrosignals and have allowed one to assume their connection with the tidal deformation processes in the Earth's crust.

The technique of the experiment was considerably improved in 1997 when conducting experiments at a distance of 356 km. Uniform series of radiation and recording with a periodicity of 3 h and a duration of 96 h were used. Signals were recorded by the system VIRS with 15-channel seismic array. It has allowed us to construct a correct spectrum on a uniform grid without secondary maxima and to choose time series of amplitudes and phases from channels with the greatest signal/noise ratio.

When determining the spectrum of time variations, we took into account the fact that the accuracy of measurements for various values in the time series is not equal. It is associated with a signal/noise ratio in each session and, as a rule, a decrease in the afternoon due to an increase of man-made microseismic noise. Therefore, in the search into the latent periodicity, the algorithm of Fourier transform for uniform time series with unequal accuracy points, which is based on approximation by periodic functions with the least squares method, was used. The spectrum component amplitude with a period T was determined from the minimization functional:

$$W_i = \sum_{n=1}^{N} \left(\frac{A_{in}}{\sigma_{in}}\right)^2 \left(\varphi_i(n\tau) - S_{\varphi_i}(T)\sin\left(\frac{2\pi n\tau}{T} + \alpha_i\right)\right)^2; \qquad (2)$$

where W_i is a functional for the time series of variations of the phase φ_i, N is the number of sessions, τ is a time step between consecutive sessions, T is a period, $S_{\varphi_i}(T)$ is the amplitude in a spectrum of time variations of the

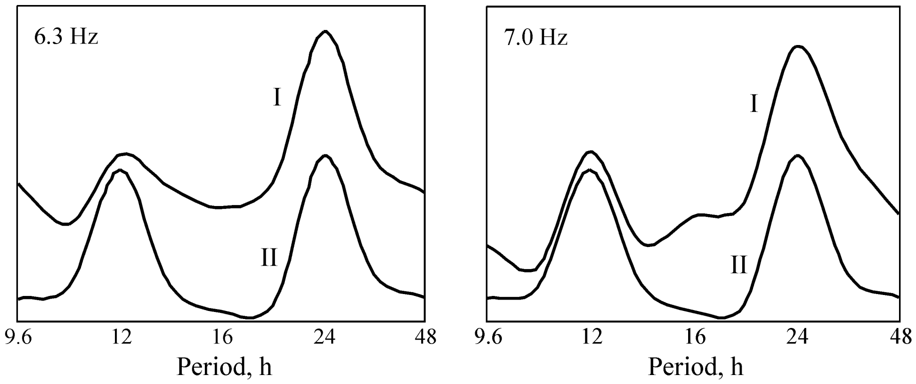

Figure 6. An average spectra of variations of vibrosignal parameters (I) and tidal variations of gravity (II). Vibrator CV-100, frequencies 6.3, 7.0 Hz, distance 356 km

phase for the period T, α_i is a spectral component phase, A_{in} is a harmonic signal amplitude in this channel in the n-th session, σ_{in} is a microseismic noise dispersion in this channel in the n-th session.

Spectral components for all time series of amplitudes and phases were determined in an interval of periods from 9.6 h till 48 h. Further, as in the processing in the previous experiment, a spectrum of each time sequence was normalized to a maximum. The normalized spectra were averaged, and a spectrum of time parameters averaged for all time series of (1) was obtained.

The averaged spectra of time variations for amplitudes and phases of harmonic vibrosignals of frequencies of 6.3 Hz and 7.0 Hz, and their comparison with a spectrum of variations of acceleration of gravity are given in Figure 6. Both spectra contain maxima with periods of 12 h and 24 h, thus repeating the results of the previous experiment. Due to uniformity of the time series, the maxima of tidal variations of gravity were obtained. Width of spectral lines width was determined by the overall duration of the experiment (96 hours) and allows us to detect the daily and the semidiurnal periodicity. The maxima of the variations of amplitudes and phases of vibrosignals are above the general noise component of the spectrum. Estimates for 24-hour and 12-hour periodicity of variations of signal amplitudes give a value of 3 %, and the corresponding value of the phase variations is approximately 1.5 degrees, which is close to the results of recording at a distance of 430 km.

The presence in the spectrum of variations of the parameters of harmonic signals, the components, which are characteristic of tides, may be the major criterion of their connection with the Earth's tides. This enables us to assume that the revealed variations of the parameters of vibroseismic fields are caused by deformation processes due to the Earth's tides, which change velocities of seismic waves.

The obtained estimates of amplitudes of 12-hour and 24-hour periodicity in the variations of the parameters of seismic signals make it possible to estimate the effect of the Earth's tides on the seismic waves arrival times and velocities at distances of 356–430 km. At frequencies of 6–7 Hz, a change in the signal phase by 1–2 degrees is associated with a time delay of 0.5–1 ms. Characteristic propagation times of P- and S- waves for a distance of 356 km are about 53 s and 94 s, respectively. Therefore, the influence of the Earth's tides on the seismic waves velocities for a distance of 356–430 km may be characterized by the results of the experiments as relative changes of velocities $\delta V/V \sim 10^{-5}$–10^{-6}. This estimate is higher because in seismological investigations and, in particular, in experiments on vibroseismic monitoring of the Earth's crust, it is impossible to exclude the influence of other natural factors (temperature, pressure, etc.) having the daily periodicity on the processes of radiation and recording of vibroseismic signals. Thus, the experiments enabled us to decrease by an order the magnitude of expected effects of the tidal deformation processes on the velocity of seismic waves in the Earth's crust.

3. Experiments "Circle" and "Baikal"

In 2000–2004, large-scale experiments on active vibromonitoring were organized in the regions of Novosibirsk and lake Baikal with the use of seismic vibrators and mobile recording systems.

In 2002, an experiment called "Circle" was started. The recording of the wave field of the powerful vibrator at azimuthally-varying directions at the same distance from a source was carried out in this experiment. Nine recording points were located at regular intervals on a circle of diameter of 300 km around the vibrator. The influence of azimuthal heterogeneity of the Earth's crust in the region of installation of the vibrator on its wave field was investigated in this experiment. The region of 150 km radius around the vibroseismic test site Bystrovka is an area where various geological structures are in contact: the Biysk–Barnaul depression in the south–southwest, Salair range in the east–southeast, Tom–Kolivan folded zone in the northeast, the West-Siberian plate in the northwest.

The experiment was aimed at the following. The first objective was to investigate the wave field of the vibrator in regions with various geological structures, to determine conditions of propagation of the main types of waves. Second, to study the structure and azimuthal heterogeneity of the Earth's crust in this region. The third objective was the full-scale modeling of the vibromonitoring system in a region of 100,000 km^2.

The scheme of the experiment "Circle" is given in Figure 7, where the red square is the vibrator CV-100, the red triangles are mobile recording complexes VIRS, ROSA.

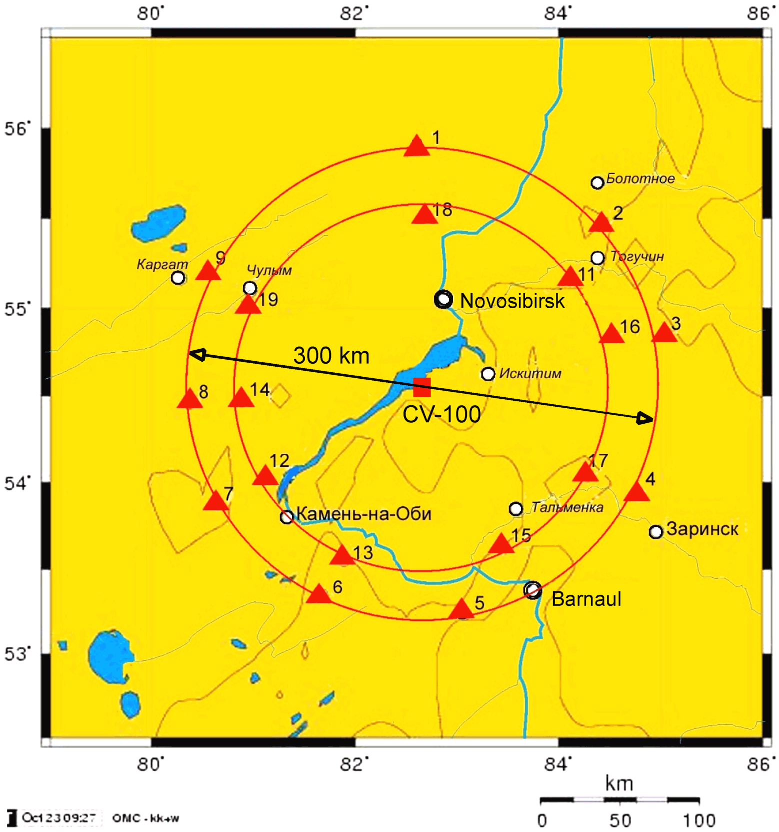

Figure 7. The scheme of experiment “Circle”

Vibrational seismograms for each azimuthal direction with well-defined arrivals of the main types of waves were obtained in the experiment. In the first arrivals, Pg- and Pn-waves at various azimuths from the source were investigated. These waves arrived with a delay of 1.5–2 s at a distance of 150 km and carried information about the location of the Moho boundary in this region.

The second stage of the experiment “Circle-2” was performed in 2003. Signals were recorded at nine points of a circle of 240 km diameter and the same azimuths, as in the previous experiment. The choice of a distance of 30 km between recording points was due to necessity to analyze changes of the arrival times of Pg- and Pn-waves in the first arrivals to determine variability of the characteristics of the Earth's crust and the Moho boundary depth at various azimuths from the source. We are now planning to carry out the azimuthal recording of the vibrator wave field on a circle of 500 km diameter to determine the azimuthal heterogeneity of characteristics of the Earth's crust-upper mantle boundary in this region.

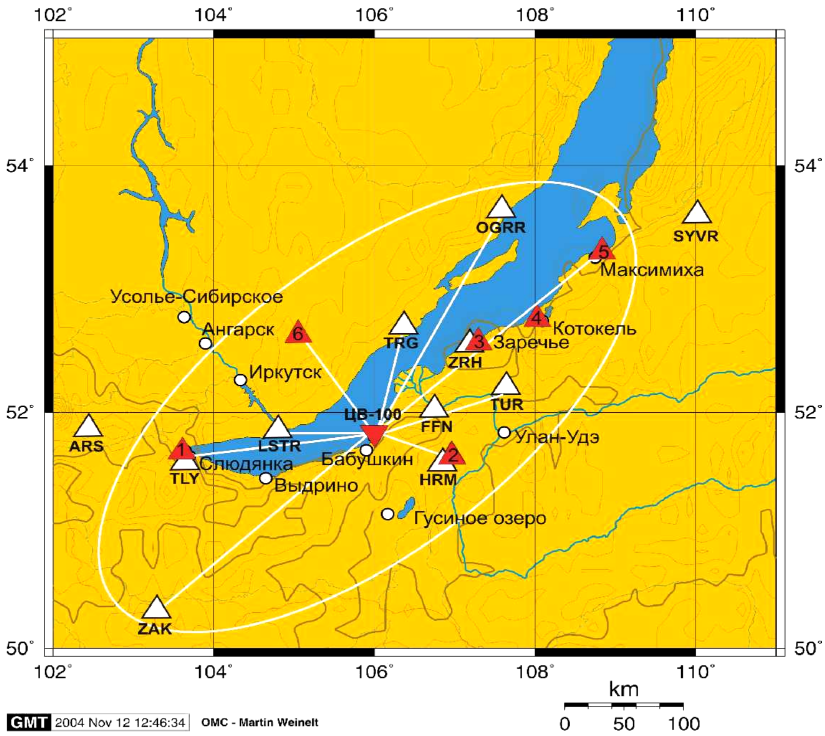

Figure 8. The scheme of experiment "Baikal"

Active vibromonitoring with the use of stationary wave fields of the vibrator in a seismic-prone zone of lake Baikal was for the first time started in 2003 in the experiment "Baikal". The experiment technique are based on the use of harmonic signals of the vibrator and principles of vibroseismic interferometry. A stationary wave field with constant amplitudes and phases of oscillations is formed at each point of a medium when the vibrator radiates harmonic signals. Changes in the zone of concentration of the stresses and earthquake preparation result in a change in the characteristics of a stationary wave field on the surface where seismic signals are recorded.

The scheme of the experiment "Baikal" is given in Figure 8, where the vibrator CV-100 (red square), mobile recording complexes (red triangles) and local seismic stations (white triangles) are shown.

In the experiment "Baikal", the field works in the southern part of Baikal were carried out. The debalance vibrator CV-100 was used as a source. It is installed on Baikal vibroseismic test site near Babushkin. Signals were recorded at the two points: at seismic station Talaya, Sludyanka (at a distance of 163 km from the source) and at seismic stations of Hurumsha (at a distance of 68 km from the source). The recording complex VIRS-M was used at seismic station Talaya with five three-component seismometers. The recording complex ROSA with four three-component seismometers was used at seismic station Hurumsha.

Harmonic signals of the vibrator were recorded in a frequency range of 6–10 Hz with a step 0.5 Hz. Frequencies with a maximal signal/noise ratio were chosen. The spectra of harmonic signals were obtained at each point. Repeatability of the amplitude-phase characteristics of the recorded wave field in a series of sessions of radiation of the harmonic signals was shown. Vibrational seismograms at both recording points were also obtained. The main types of waves were detected.

In 2004, the monitoring with harmonious signals in a seismic-prone zone of Baikal was continued. Recording points were chosen near to seismic stations Zarech'e, Kotokel and Maksimikha at distances of 115, 178, 248 km from a source, respectively. The complexes VIRS-K and ROSA were used. Sessions of monitoring were carried out during three days, with the use of harmonic and sweep-signals of the vibrator. Four sessions of the vibrator in the monochromatic radiation mode and with frequencies 6.5, 7.0, 7.5, 8.0, 8.5, 9.0 Hz were performed, and, also, four sessions in the mode sweep-signals and with frequencies 6.25–10.059 Hz with duration 3272 s. Spectra of harmonic signals and vibro-seismograms were received for comparison with seismograms from seismic stations of the regional network. As a result, the database of the experiment, including 432 files of waveforms is being created.

The purpose of the experiments in question was to show the possibility of stable recording of harmonic signals from the vibrator on the test site of Babushkin both with the use of specialized recording complexes VIRS-M and ROSA, and with routinely available seismic stations included in the regional network. The data from these seismic stations have allowed us to organize continuous monitoring of the Baikal seismic-prone zone with the use of periodic sessions of radiation of harmonic signals from the vibrator.

Conclusion

The experiments with the powerful seismic vibrators aimed at the sensitivity of the active monitoring system with the 100-ton vibrator were carried out. The experiment has shown that such system makes it possible to detect relative variations of the seismic wave velocities of order 10^{-5}–10^{-6} in an area of 300–400 km around the source. The experiment "Circle" has demonstrated the full-scale prototype of the active monitoring system for the region of 100,000 km^2 on the basis of one 100-ton vibrator and several mobile recording systems.

Now vibroseismic monitoring of 550 $\times$ 250 km area is carried out in the Baikal seismic-prone zone with the use of mobile recording complexes and seismic stations of the regional network. The use of the data from these seismic stations makes it possible to organize continuous monitoring of the

Baikal seismic-prone zone with periodic sessions of radiation of harmonious signals from the vibrator. The results of the works are of practical importance for solving the problem of the intermediate-term forecast of earthquakes in seismic-prone areas, and, in particular, in the Baikal seismic-prone zone. Since 2003 till present, the Buryat Branch of the Geophysical Survey of SB RAS and the Institute of Geology SB RAS in Ulan-Ude carry out a continuous monitoring using the vibroseismic interferometry technique on seismic stations of the regional seismic network.

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