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Feasibility of Uusing Molecular-Electronic Seismometers in Passive Seismic Prospecting: Deep Structure of the Kaluga Ring Structure from Microseismic Sounding

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Abstract—Field experiments involving molecular-electronic seismometers, along with conventional pendulum geophones, were performed to study the deep structure of the upper crust (in the area of the Kaluga ring structure) by passive seismic methods. The microseismic sounding survey was carried out along a geophysical profile crossing the central part of the structure with simultaneous data acquisition by molecular-electronic and conventional seismometers at each measurement point. Experimental data on the propagation of Rayleigh waves along the curvilinear surface have been collected. The feasibility of using molecular-electronic seismometers for passive seismic studies has been confirmed by the results of comparative analysis of the vertical geophysical cross sections, which reveal upper crustal heterogeneities, and by the results of a series of laboratory tests.

Keywords: molecular-electronic seismometers, microseismic sounding, surface waves, deep underground structure, Kaluga ring structure

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INTRODUCTION

The innovative molecular-electronic seismometers developed in Russia (Agafonov et al., 2014) appear very suitable when conducting field geophysical surveys with passive seismoacoustic methods. The new seismometer designs have no high-precision mechanical elements and moving mechanical components, and this makes them reliable and stable to outer effects. These instruments do not require caging or centering of mass, and they remain operable at deviations of up to 15° from the vertical axis. Owing to this feature, installation of a molecular-electronic seismometer can be done much faster than, e.g., an SM3-OS pendulum electrodynamic seismometer; this in turn enables successful measurements even in areas where SM3-OS operation is impossible, e.g., on the sea floor (Levchenko, 2005; Levchenko et al., 2010a, 2010b). Another feature important for field studies is that molecular-electronic seismometers have a relatively light weight, small size, and low power requirements. All these features make molecular-electronic geophones very promising instruments for field works.

The operating principle of molecular-electronic seismometers with oscillating speed is based on the mechanism of convection-diffusion charge transfer between the electrodes of the converter under when induced convection occurs in the presence of an external mechanical effect (Abramovich et al., 1999; Shabalina et al., 2014). Electrolyte flowing through the converter due to external mechanical action plays the role of the inertial mass in these sensors. In the operating mode, constant electrical voltage is supplied to each electrode couple of the converter (Fig. 1); if the liquid moves in the converter tube, the convection component of the current appears between electrodes of the converter, in addition to the the respective response in the form of an electrical signal read from the electrodes.

Recently, molecular-electronic seismometers have been applied in solving seismic survey problems in volcanology and in organizing temporary seismic networks (Koulakov et al., 2014) to measure the kinematic characteristics of elastic waves, although these methods require quite accurate seismic instruments to be used. Conversely, amplitude methods of seismic survey (Gorbatikov, 2006; Zhostkov et al., 2015) do not require highly reliable primary converters that ensure stable phase-frequency characteristics and per-

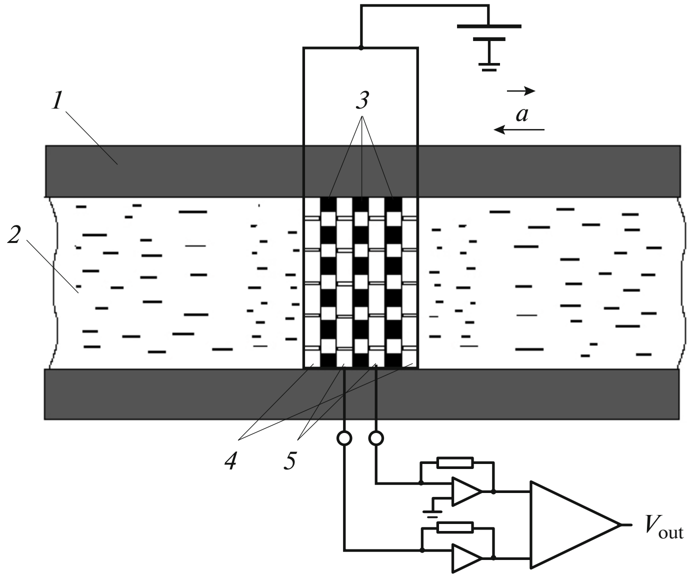

Fig. 1. Scheme of molecular-electronic converter: (*1*) ceramic tube assixed to both ends with elastic membranes that allow electrolyte to move with respect to electrodes; (*2*) electrolyte; (*3*) porous ceramic walls; (*4*) anodes; (*5*) cathodes; $\bar{a}$ is external mechanic acceleration; V_{out}, output signal.

fectly accurate determination of a signal amplitude, because they use averaged normalized signals during processing.

The microseismic sounding method (MSM), which makes it possible to trace the structure of subvertical fluid-conducting bodies in the upper and middle crust, has been successfully used in solving engineering geological problems, studying the deep structures of mud volcanoes in Taman and active faults in other regions, and in investigating certain oil-and-gas-bearing fields (Gorbatikov et al., 2008a, 2008b, 2010, 2011; Sobisevich et al., 2008, 2015; Rogozhin and Gorbatikov, 2015). In this respect, it is interesting to study the applicability of molecular-electronic seismometers in solving passive seismic survey problems.

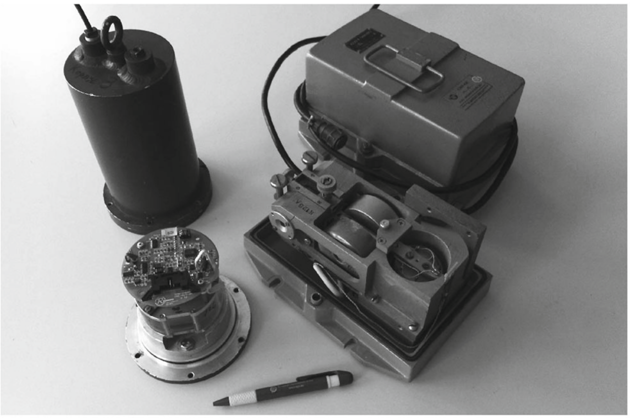

Fig. 2. SM3-OS pendulum seismometer with removed cover (right), seismometer based on molecular-electronic converter, and airtight box for marine studies (left).

MATERIALS AND METHODS

As the primary converters. we used SM3-OS seismometers and sensors based on molecular-electronic converters, which are applied, e.g., in SME seismometers manufactured by the R-sensors company (Fig. 2).

Geophysical works along the profile were done using the passive seismic survey method, namely, MSM, which is based on the assumption (Gorbatikov, 2006) that the vertical component of the microseismic field in the low-frequency band is determined by the predominant contribution of the fundamental modes of Rayleigh surface waves. Numerical studies (Gorbatikov and Tsukanov, 2011; Tsukanov and Gorbatikov, 2015) showed that local heterogeneities in the Earth's crust affect the amplitude of surface waves: domains with higher-velocity traveling of elastic waves causes a decrease in the amplitude of microseismic noise and vice versa. Remarkably, the influence of heterogeneities is seen predominantly in waves with a length approximately twice as long as the occurrence depth of the heterogeneity.

The microseismic field in this method is considered a superposition of trains of fundamental modes of Rayleigh waves with different frequency fillings, which are predominant in the natural microseismic noise of the Earth. It is also believed that the sources of these wave trains are distributed randomly in a geological setting, resulting in a diffuse character of the field.

Field works using this method imply simultaneous recording of microseismic noise at the study sites and at the base station. Then, the averaged spectra of these signals are compared to determine the relative amplitude of microseismic noise for each measurement point and every frequency of a surface wave. Using the relationship between the frequency and length of a wave, we proceed to the dimension of depth and finally obtain a 2D image of the depth distribution of contrasts in the traveling velocity of shear waves along the studied profile. Thus, svertical geophysical cross section obtained as a result of processing of the accumulated data reveals the structure of geological heterogeneities in the medium based on contrasts in seismic velocity.

RESULTS OF LABORATORY TESTS

Immediately before the experiment, all seismometers were calibrated on a certified vibration table at the Geophysical Survey of the Russian Academy of Sciences (GS RAS; Obninsk). Based on the calibration results, we plotted the sensitivity curves (Fig. 3a). Unfortunately, the vibration table at GS RAS does not allow calibration at frequencies greater than 20 Hz; nevertheless, the specifications of molecular-electronic seismometers indicate that their frequency range is 0.03–50 Hz.

In general, the sensitivity of molecular-electronic seismometers demonstrates behavior typical of this type of instruments. However, the phase characteristics of the studied converters are not stable enough. In an example of a synchronized record (Fig. 3b), we can see that phase shift of records of two similar molecular-electronic seismometers at a frequency of 0.03 Hz is up to 1 s. If the frequency is increased, the shift decreases, becoming within the limits of the measurement error.

Another important characteristic of measuring instruments that pertain to seismometers is the intrinsic noise level that determines the minimal recordable signal. The manufacturer determines the typical intrinisic noise for a seismometer based on a molecular-electronic converter (Agafonov et al., 2014), and the presented data suggest that intrinsic noise of molecular-electronic instruments ranges from −120 to −160 dB, which is fairly comparable to the characteristics of broadband seismometers manufactured by leading world companies.

Sometimes, seismic measurements have to be carried out under low-temperature conditions (Presnov et al., 2014). Below we compare records made by an SM3-OS and a molecular-electronic seismometer, with the latter being cooled (Fig. 4). In the present experiment, the minimum acceptable operational temperature of a molecular-electronic seismometer (−12°C) was almost reached, but its record was almost identical to that of a SM3-OS seismometer. If seismometers have to operate under extremely low temperatures, a denser electrolyte can be used (the operating temperature can thus be expanded to −40°C).

Let us analyze the quality of recorded seismic signals. For this, we synchronously recorded signals over two days using three molecular-electronic seismometers and three SM3-OS seismometers placed on a special concrete table unattached to the basement in a basement room of the Coordination and Prediction Center of the Schmidt Institute of Physics of the Earth, Russian Academy of Sciences (IPE RAS; Mosrentgen microdistrict, Moscow). Nocturnal records, with the sensitivity curves obtained on the calibration table at GS RAS taken into account, are shown in Figs. 5–7.

Analyzing Fig. 5 we can see that the sensitivity of molecular-electronic seismometers at high frequencies exceeds the sensitivity of SM3-OS seismometers, while at low frequencies, SM3-OS is more stable than a molecular-electronic seismometer. To illustrate this, let us consider the 0.13–1 Hz frequency band, where the compared types of seismometers show nearly equal signal levels.

Comparison of the records in Fig. 6 gives grounds for the following conclusions. First, the difference between signals recorded by different SM3-OS seismometers is much smaller than for molecular-electronic seismometers. This confirms the small change in the amplitude-frequency characteristics of the SM3-OS with time and the unstable sensitivity of molecular-electronic seismometers. The same can be concluded if we take into account the calibration curves of molecular-electronic seismometers obtained at different times. The first calibration of molecular-electronic seismometers, whose sensitivity curves are shown in Fig. 3a, was done in 2013 using the same table at GS RAS as in 2015. It should be noted that the amplitude-frequency characteristics of the used instruments changed slightly within two years. Figure 7 shows the signal recorded by a molecular-electronic seismometer, but processed with both the 2013 and 2015 calibration curves.

Second, the difference between records of molecular-electronic seismometers does not exceed 10%, i.e., the signal was generally recorded correctly, as well as SM3-OS instruments. In this respect, the question arises: why do different types of instruments being calibrated on the same vibration table and by the same technique considerably differ in amplitude when the same signals are recorded. For example, the amplitude of a signal recorded by an SM3-OS in Fig. 6 is about 6 μm/s, while that for molecular-electronic seismometers is 8.5 μm/s; note that approximately the same ratio between signal amplitudes recorded by two types of instruments was also preserved in other frequency bands and in other time intervals.

This can be explained by the fact that calibration took place at room temperature, while the compared

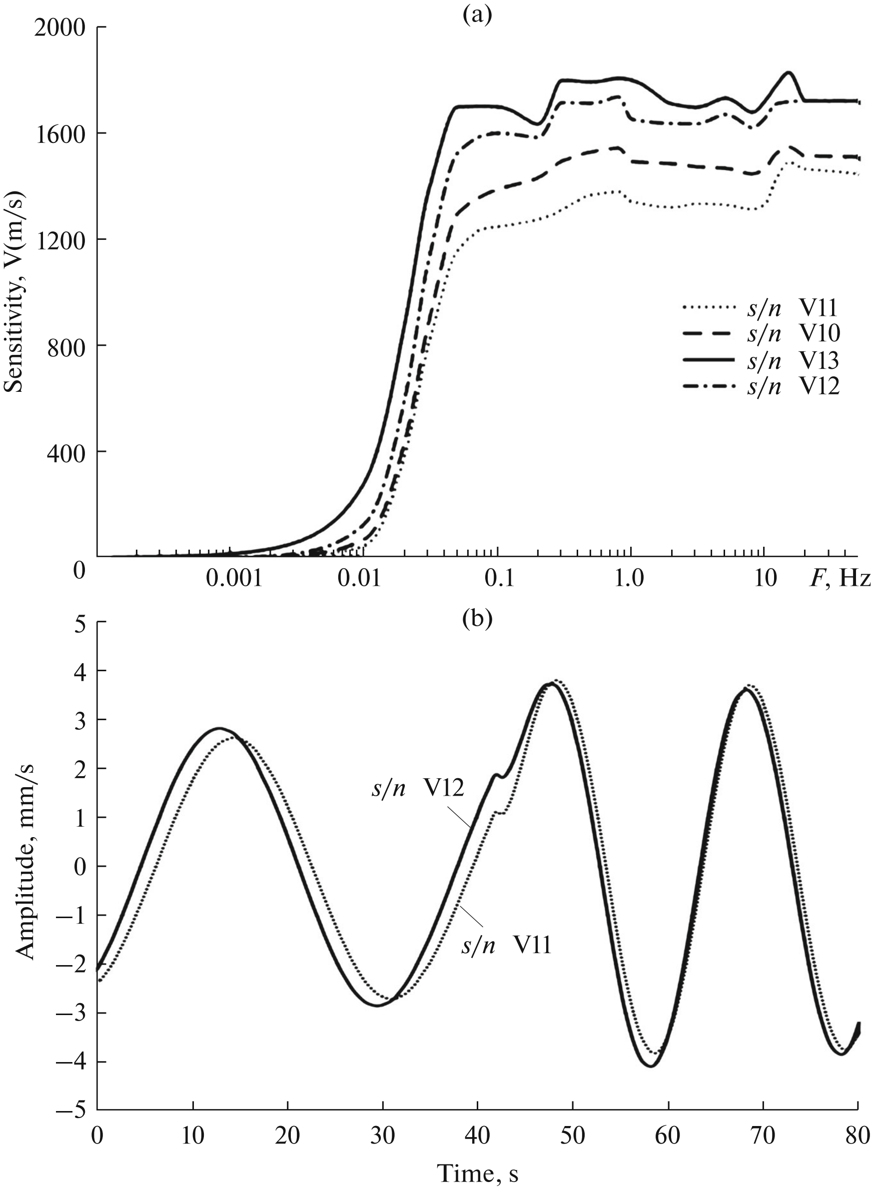

Fig. 3. Amplitude-frequency characteristics of molecular-electronic seismometers (GS RAS) (a) and fragment of synchronized records from two seismometers (GS RAS) (b).

records were obtained at temperatures ranging from −5 to 0°C, and temperature compensation was not applied. On the other hand, this difference might be caused by the nonlinear character of sensitivity of molecular-electronic seismometers, because calibration was done with strong vibrations, while the signals in the compared records done on a table were weak.

Thus, the unstable phase and amplitude characteristics of molecular-electronic seismometers, as well as the need to take into account temperature correction, complicate the application of this type of instruments to solve classical seismic survey problems, despite the excellent operational properties mentioned in the Introduction.

Nevertheless, there are problems where accuracy of signal phase recording is not necessary (because the averaged spectra of signals accumulated over a long time interval are used) and there are no strict requirements on the stability of the amplitude-frequency characteristics (because analysis of field data implies the use of relative amplitude). The second condition implies that the difference between normalized signals must be minimal: for molecular-electronic seismometers, this condition is satisfied with an error comparable to that of an SM3-OS (Fig. 8).

Figure 8 shows the ratios between the spectra of 5-min signals recorded by instruments used in field works as portable stations and the spectra of signals

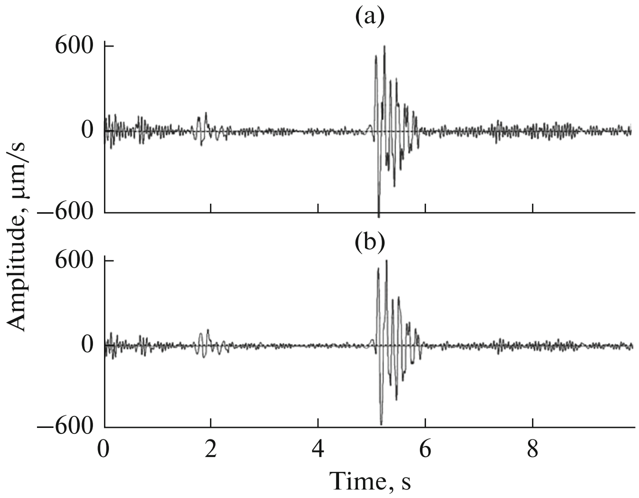

Fig. 4. Comparison of records of SM3-OS (a) and molecular-electronic seimsometer (b) after cooling of latter in freezer. (a) $T \sim 15°C$; (b) $T \sim -10°C$; filtering in 0.5–10 Hz band.

recorded by base stations. In accordance with the MSM, we used data from checking the compared instruments as calibration curves. Since all instruments were placed on the same table, signal spectra from portable stations were referred to the spectrum of a time-shifted signal of a base station in order to obtain nonunity ratios. Thus, on one vibration table we have carried out the experiment that can be interpreted as application of MSM in the case when two seismometers (a SM3-OS and a molecular-electronic one) are used at the basic station, while four (two SM3-OS and two molecular-electronic ones) at the portable station. According to MSM, the ratios obtained in Fig. 8 are interpreted as the final result for one observation point. Analyzing these data, we can conclude that molecular-electronic seismometers can be successfully applied during geophysical survey by the MSM, because in the low-frequency region the dispersion of results obtained using molecular-electronic seismometers is even smaller than those when using SM3-OSs. Similar results are also obtained in high-frequency region.

It should be emphasized that in the low-frequency region (as is seen particularly well in the vicinity of 0.16 Hz), the ratios between the spectra obtained by molecular-electronic seismometers and SM3-OSs differ considerably (by up to 15%), which can be related to better sensitivity of the SM3-OS in the low-frequency region. Another important factor may be that the results obtained with the SM3-OS are similar—i.e., the instrument yielding a higher value does so in the entire frequency range, whereas this is not the case with molecular-electronic seismometers. This takes place, e.g., in the vicinity of 0.46 Hz.

However, we should take a critical look at the obtained results, because averaging over an ensemble of only two instruments may be inaccurate. Conversely, averaging over time with the MSM approach on the same table described above is impossible, because the ratios between the spectra in the MSM characterize the constant properties of the medium under study, whereas in the described approach, these ratios are random. In fact, averaging over time is done in field-based sounding using the MSM and is described in the following section.

FIELD EXPERIMENT

The main problem of this study was to test the applicability of molecular-electronic seismometers in field conditions during a passive seismic survey. For this, we chose the quite well-known object in the central Kaluga ring structure. In 2009, 2D geophysical surveys with the MSM yielded data on the structure of a relatively small part of the Kaluga ring structure to a

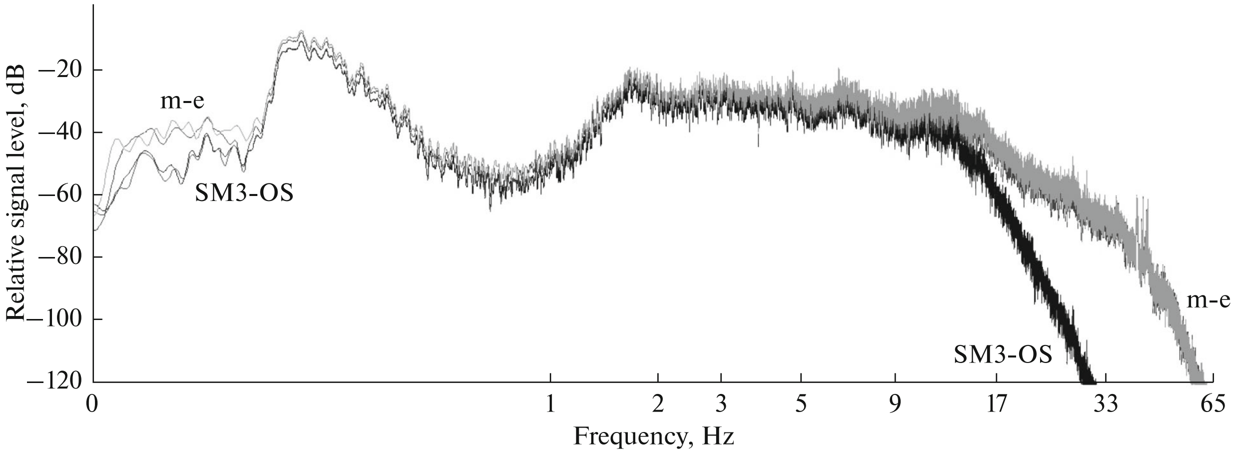

Fig. 5. Comparison of spectra of 20-min-long synchronous record by two seismometers: SM3-OS and two molecular-electronic seismomemters (m-e). Records were obtained on concrete seismic table at laboratory of IPE RAS.

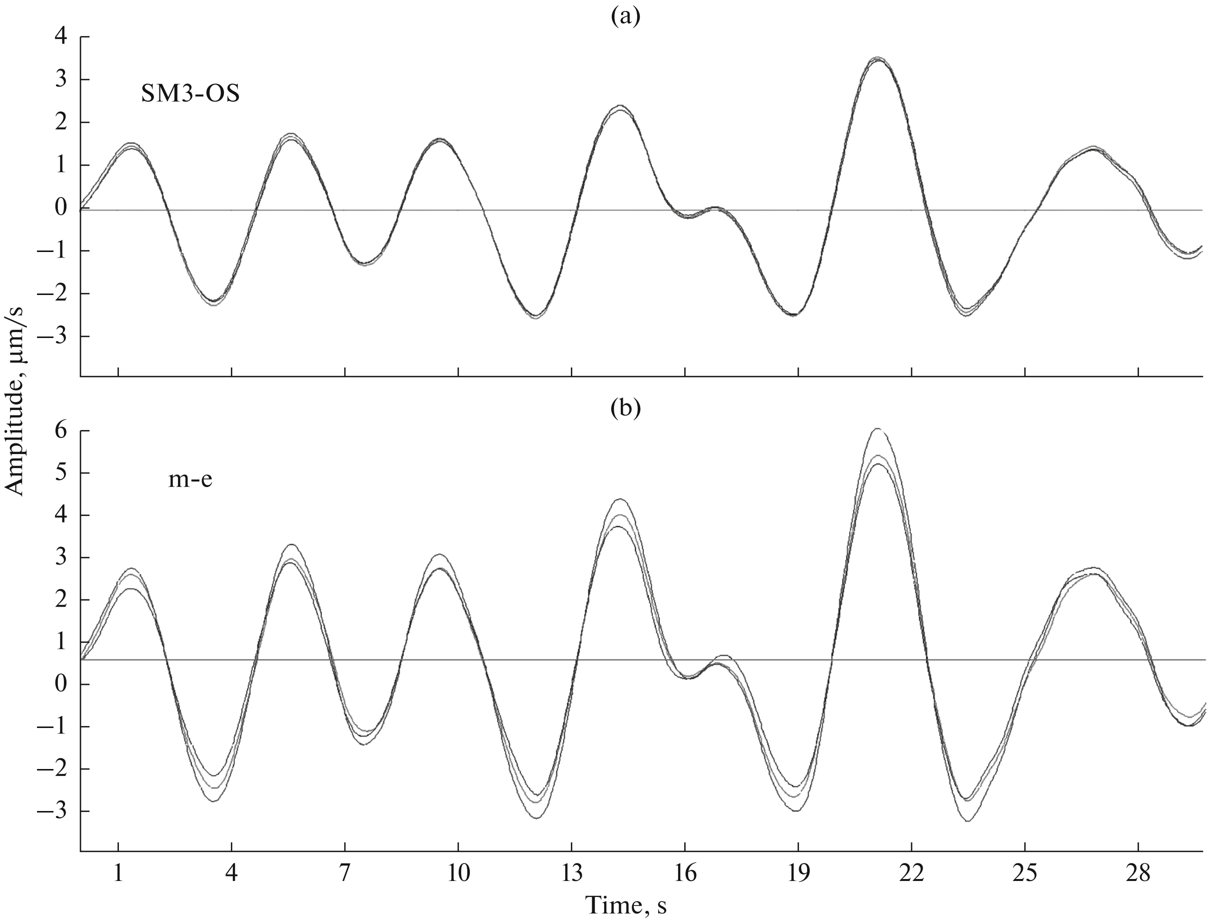

Fig. 6. Comparison of records of three SM3-OS (a) and three molecular-electronic seismometers (b). Records were obtained on concrete seismic table at laboratory of IPE RAS. Filtering in 0.13–1 Hz band.

depth of 10 km; in addition, subvertical structures of the "inner ring" with a characteristic southward dip were revealed (Malovichko et al., 2010).

The Kaluga deep ring structure (DRS) is one of the most well-studied DRSs idmtified in the central East European Craton, in the northwestern periphery of the Voronezh anteclise; it is a rounded depression 15–17 km in diameter, sinking into rocks of the crystalline basement to a depth of up to 500 m. The depression is filled with allogenic breccia and suevites up to 90 m thick, and fragments of sedimentary and crystalline rocks covered by Vendian, Middle Devonian, and Lowe Carboniferous terrigenous-carbonate deposits (the total thickness is more than 1000 m). In the central part of the depression, a rise 200 m in height relative to the bottom and characteristic of impact structures hs been outlined, as well as an annular socle bar up to 3.5 km wide (Marakushev, 1981).

Technically, works along the profile repeated the measurements of 2009, but the difference was that in the present case, seismic signals were recorded at all points simultaneously by pendulum and molecular-electronic seismometers. Subsequent comparison of the obtained geophysical cross sections, which were constructed from data from different types of primary converters, aimed to determine the applicability limits for molecular-electronic seismometers in amplitude passive seismic survey methods.

The 2015 profile includes eight measurement points located along a straight line with a span of about 300 m (Fig. 9); the total length of the profile is 2.3 km. In the areas of points p6 and p7, the profile crosses the inner ring of the Kaluga ring structure; additionally, there is a ravine in the area of points p4 and p5 (Fig. 10)—this irregularity of the relief affects Rayleigh surface waves and should be taken into consideration in a more detailed study.

In accordance with the MSM technique, the base station was placed at a considerable distance from the profile (~2.7 km) in order to avoid possible noise from local technogenic sources that may be falsely interpreted as desired microseismic signal during processing. However, this distance should not be too large, so that microseismic fields in the stations along the profile and at the base station show consistent compositions.

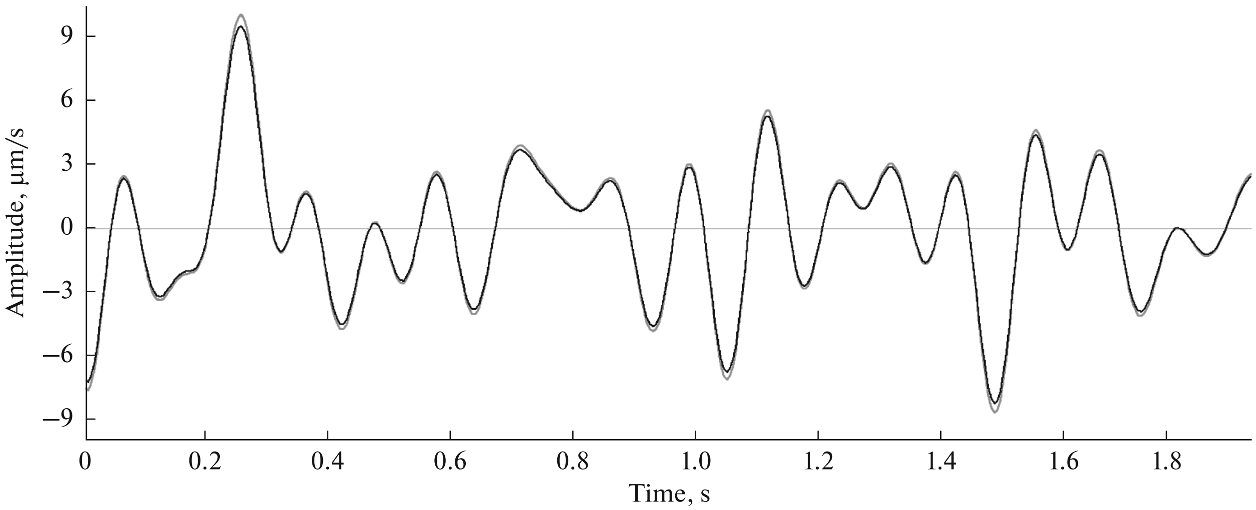

Fig. 7. Comparison of signals recorded by molecular-electronic seismometer and obtained using calibration curves of 2013 (gray) and 2015 (black).

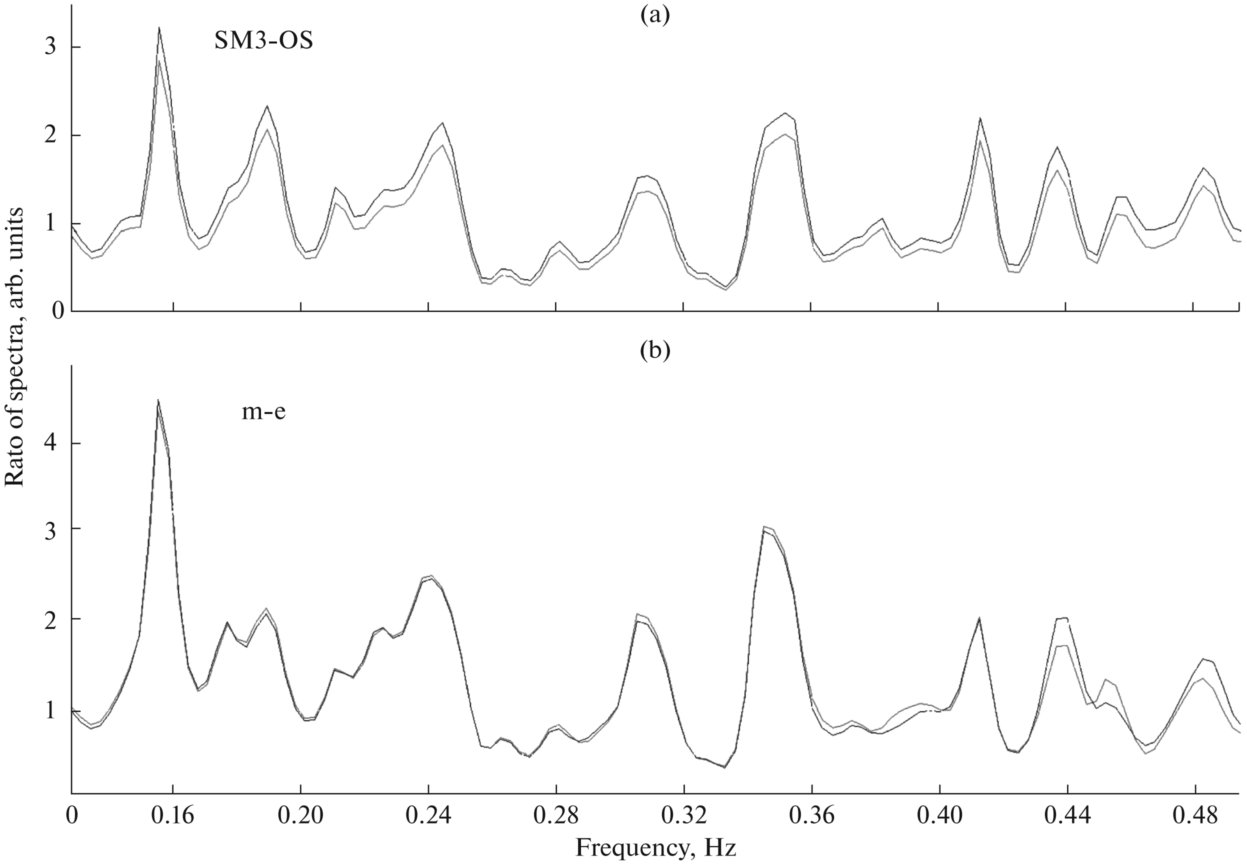

Fig. 8. Comparison of ratios of spectra of synchronous signals recorded by instruments used in field studies as portable stations (see below) and spectrum of time-shifted signals (also synchronous) recorded by instruments used as base station. Frequency band is 0.13–0.5 Hz.

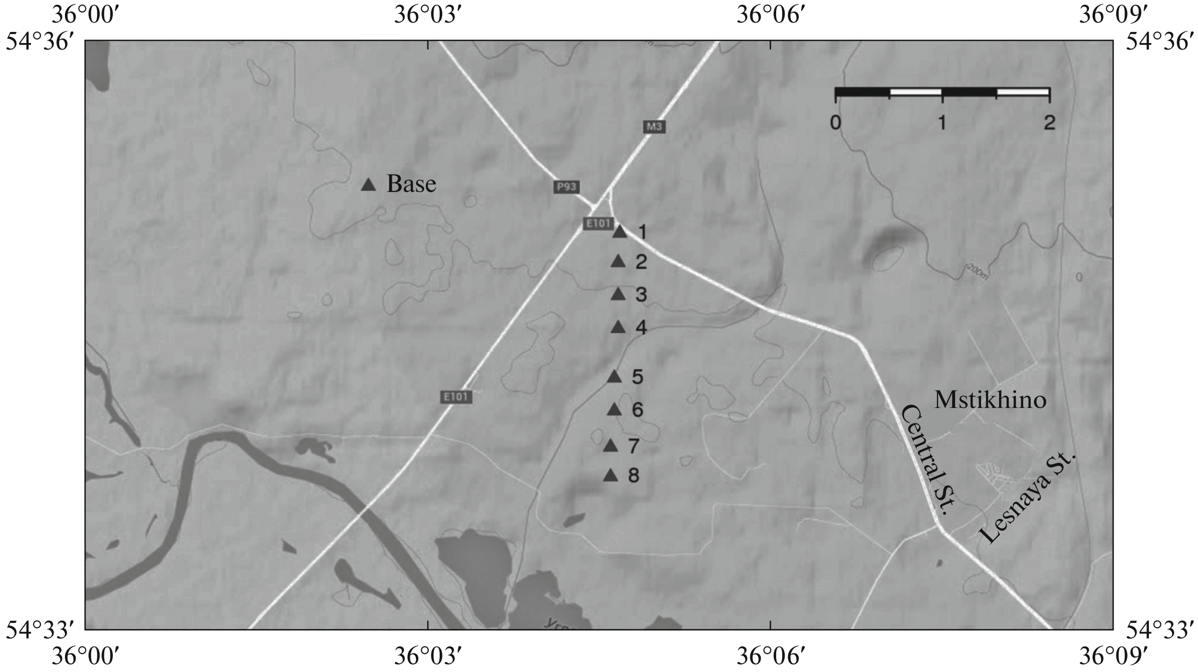

Fig. 9. Map of area where field works were conducted, with points where base and portable stations were installed.

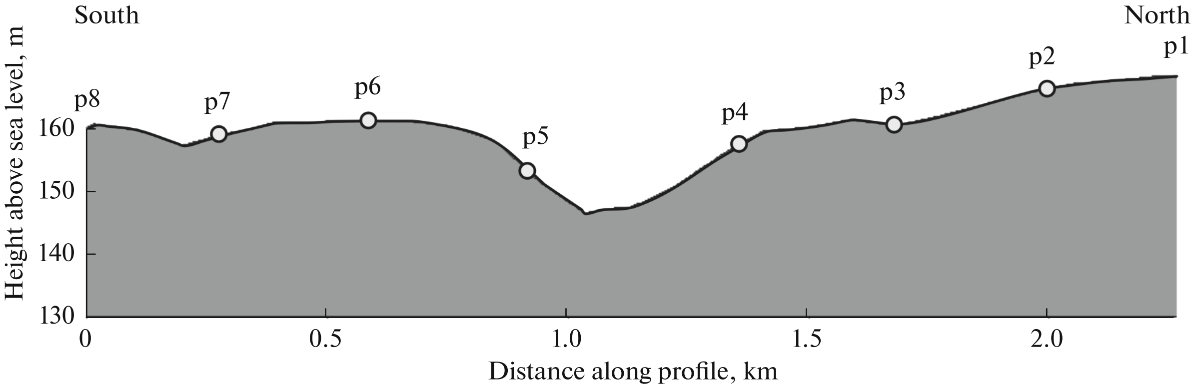

Fig. 10. Vertical cross section of elevation model along profile with points of geophysical measurements.

The measurements along the profile under study were in fact coducted twice, because at every point, including the base one, records were made by two sets of seismometers (SM3-OS and molecular-electronic), since the aim of this experiment was to test the performance of molecular-electronic seismometers in real-scale studies.

Field works in the area of the Kaluga ring structure were carried out on November 21–22, 2015. During the measurements along the profile, we used instrumental complexes consisting of three-channel recorders of Reftek-130b-type, SM3-OS broadband seismometers, and seismometers based on molecular-electronic converters. At every observation point, seismometers were placed at specially prepared pits about 0.5 m in depth, strictly aligned using a level, and then buried to reduce noise related to wind and other sources. Sensors at the base station were set up on in the first day and were not replaced during the entire period of the experiment. Measurements at each point were carried out for at least 2 h.

All measuring complexes were checked on the same vibration table a few days after the expedition, at the Coordination and Prediction Center of IPE RAS. The data were recorded over two days and allowed us to obtain the calibration coefficient of acceptable quality, which is related to the broadband microseismic noise due to the local proximity of a segment of the Moscow Ring Road.

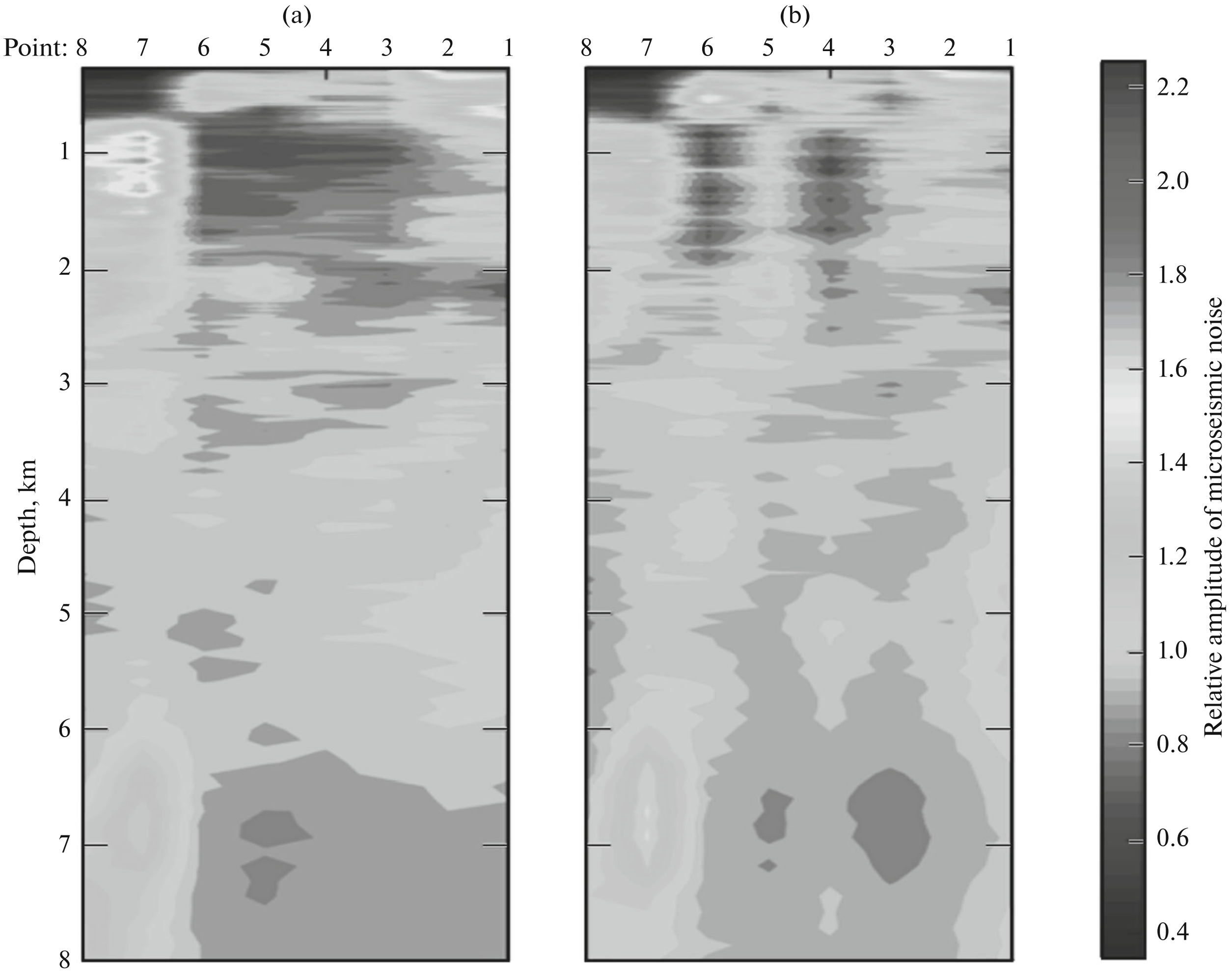

Fig. 11. Vertical geophysical cross sections along studied profile obtained with SM3-OS (a) and molecular-electronic seismometers (b). Colored scale indicates relative amplitude of microseismic noise. Warm tones correspond to zones of lower seismic velocities, where rocks are more fractured and porous, hence conducting fluids. Colder tones outline zones of relatively higher seismic velocities, which can be attributed to more solid and, hence, weakly permeable rocks.

To illustrate the results of field works, Fig. 11 shows two geophysical cross sections along the studied profile (see Fig. 9); they were obtained by the classical MSM (Gorbatikov, 2006) with only SM3-OS and molecular-electronic seismometers.

The results convincingly show that all the characteristic geological units that can be clearly distinguished using pendulum seismometers with the MSM are also identified by molecular-electronic seismometers. In Fig. 11, these objects are low-velocity zones: near-surface ones at points p1 and p2 and at a depth of 0.5 km; at point p5, at a depth of 2 km; at point p6, at a depth of 0.5 km; at points p7 and p8, at depths of 0.8–2.5 and 6–7.5 km. There were also high-velocity zones: at a depth of 0.5–2 km at points p3 to p6 and at a depth of 6–8 km at points p1 to p6.

Nevertheless, the results differ from each other; in order to better illustrate this, let us present the difference between intensity values (Fig. 12) obtained using SM3 pendulum seismometers $I_s(r,z)$ and molecular-electronic seismometers $I_e(r,z)$, as calculated by the standard formula:

$$\Delta(r,z) = \left|\frac{I_s(r,z) - I_e(r,z)}{[I_s(r,z) + I_e(r,z)]/2}\right| 100\%.$$

Discrepancies exceed 10% only in a few areas, and the main “errors” are distinguished in the frequency region of about 1 Hz, moreover, at three points out of eight. Since all these errors are not systematic, their presence can be explained by inaccurate installation of the pendulum seismometers. It is undoubted that SM3-OS seismomemters, rather than molecular-electronic ones, were installed in such a way, because installation of pendulum instruments is complicated and requires, in addition to thorough leveling, that the protective covering be removed for uncaging (when removing the protective cover, dirt may end up on the

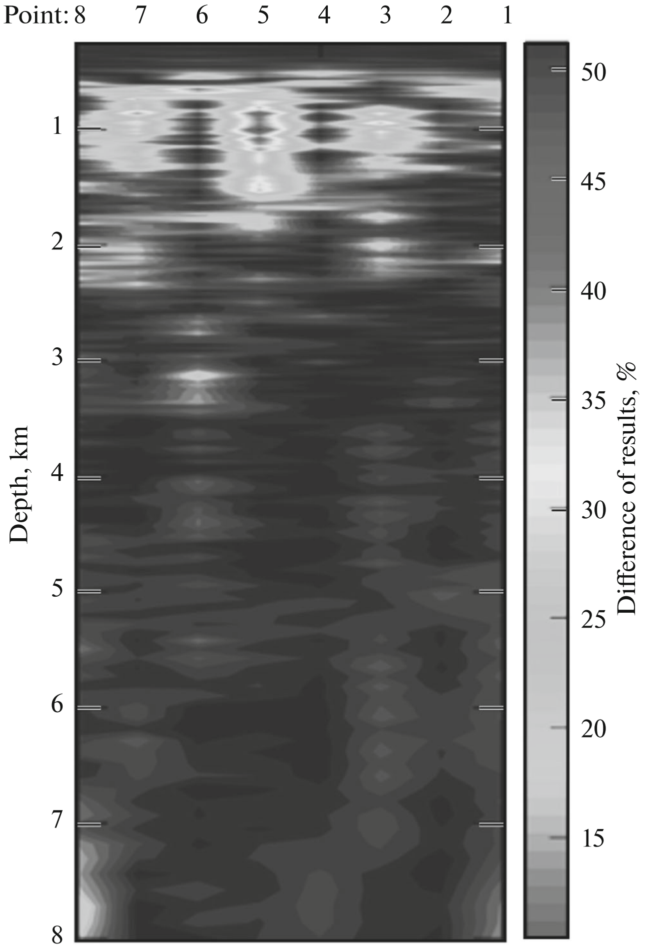

Fig. 12. Difference (in percent) of reconstruction results of geophysical cross section obtained with different types of seismometers.

sensor element—or water drops, in our case, because there was heavy rain during works at points p4 to p8. In contrast, installation of a molecular-electronic seismometer is relatively simpler and does not require high leveling accuracy.

CONCLUSIONS

The high accuracy of absolute and relative seismic measurements by SM3-OS pendulum seismometers under the observatory conditions has been verified.

In the high-frequency region, seismometers with molecular-electronic coverters record signals more accurately than SM3-OS seismometers owing to the higher sensitivity; in this respect, molecular-electronic seismometers are preferable when solving engineering and geophysical problems that require accurate determination of the characteristics of near-surface layers. Conversely, when solving problems related to studies of deep structures (deeper than 10–15 km) pendulum instruments should be used, because molecular-electronic seismometers demonstrate too unstable sensitivity in the low-frequency region.

It has been found that molecular-electronic seismometers, despite certain shortcomings of the phase and amplitude characteristics, can be successfully applied in seismic surveys using passive geophysical methods and involving time-averaged relative amplitudes, e.g., the microseismic sounding method.

It has been shown that molecular-electronic seismometers have characteristics sufficient to replace SM3-OSs in geophysical studies using passive seismic surveys (with accumulation). To a certain extent, this is caused by errors related to incorrect installation of an instrument, because molecular-electronic seismometers are less sensitive to installation quality compared to pendulum instruments. Convenience of operation, low cost, and acceptable accuracy make molecular-electronic seismometers ideal instruments for geophysical studies by methods similar to the MSM.

Based on the results of comparative analysis of the obtained geophysical sections, which expand our knowledge about the deep structure of the central Kaluga ring structure, the applicability limits for electrochemical seismometers in passive seismic studies have been established.

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