Journal of Applied Geophysics 49 (2002) 91–100

JOURNAL OF APPLIED GEOPHYSICS

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Correction of the electromagnetic monitoring data for tidal variations of apparent resistivity

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Received 25 January 2000; accepted 8 September 2000

Abstract

The use of the ELF (extremely low frequency) radio station "Zevs" for the study of the stress–strain state of geological media is considered. Analysis of prior research on the connection between tidal phenomena and apparent resistivity ρ_a variations at earthquake prediction sites are made. In the ELF range experimental measurements of artificial electromagnetic field impedance and the results of calculation of tidal deformations are considered. A high degree of correlation of ρ_a values and vertical deformations of the Earth surface ΔH are noted. Diurnal ρ_a changes of 7% due to tidal phenomena, were recorded with measurements accuracy of $\pm 0.6\%$. To increase the reliability of earthquake prediction it is necessary to correct the electromagnetic monitoring data for tidal effects using correlation equations between ρ_a and ΔH.

Keywords: Tide; Apparent resistivity; Electromagnetic soundings

1. Introduction

The electrical resistivity of rocks (ρ) is characterized by high sensitivity to the stress–strain state of geological medium. This is connected to the influence of a rock's structural features, its degree of water saturation and the mineralization of the water. Under the effect of external pressure, the medium is deformed, the characteristic pore space and cracking varies, fluid motion occurs and, as a result, the rock resistivity varies (Rikitake, 1976).

The dependence of ρ to pressure variation is used to study the stress–strain state of the media in mines and for the prediction of mining tremors by electrical prospecting methods. Apparent electrical resistivity, ρ_a, can vary in mines by more than a factor of 10. Before mining tremors, the value of ρ_a usually decreases, although an increase of ρ_a has also been observed (Stopinski and Teisseyre, 1977).

The application of electric and electromagnetic soundings to earthquake prediction is based on the study of the time evolution of ρ_a because it gives information about rock resistivity changes at depths where the influence of seasonal and meteorological factors are smaller. The results of research by deep electrical investigation show that ρ_a changes are usually observed during the period of several months before an earthquake (Barsukov, 1973). The sizes of

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0926-9851/02/$ - see front matter
PII: S0926-9851(01)00101-X

ρ_a variations prior to earthquakes are from several to 10–20% (Rikitake, 1976). To measure such changes of ρ_a values, it is necessary to obtain a highly accurate measurement.

The experience of application of the electrical soundings using alternating inductive fields shows that a high accuracy of measurements in a wide band of frequencies can be accomplished by the use of

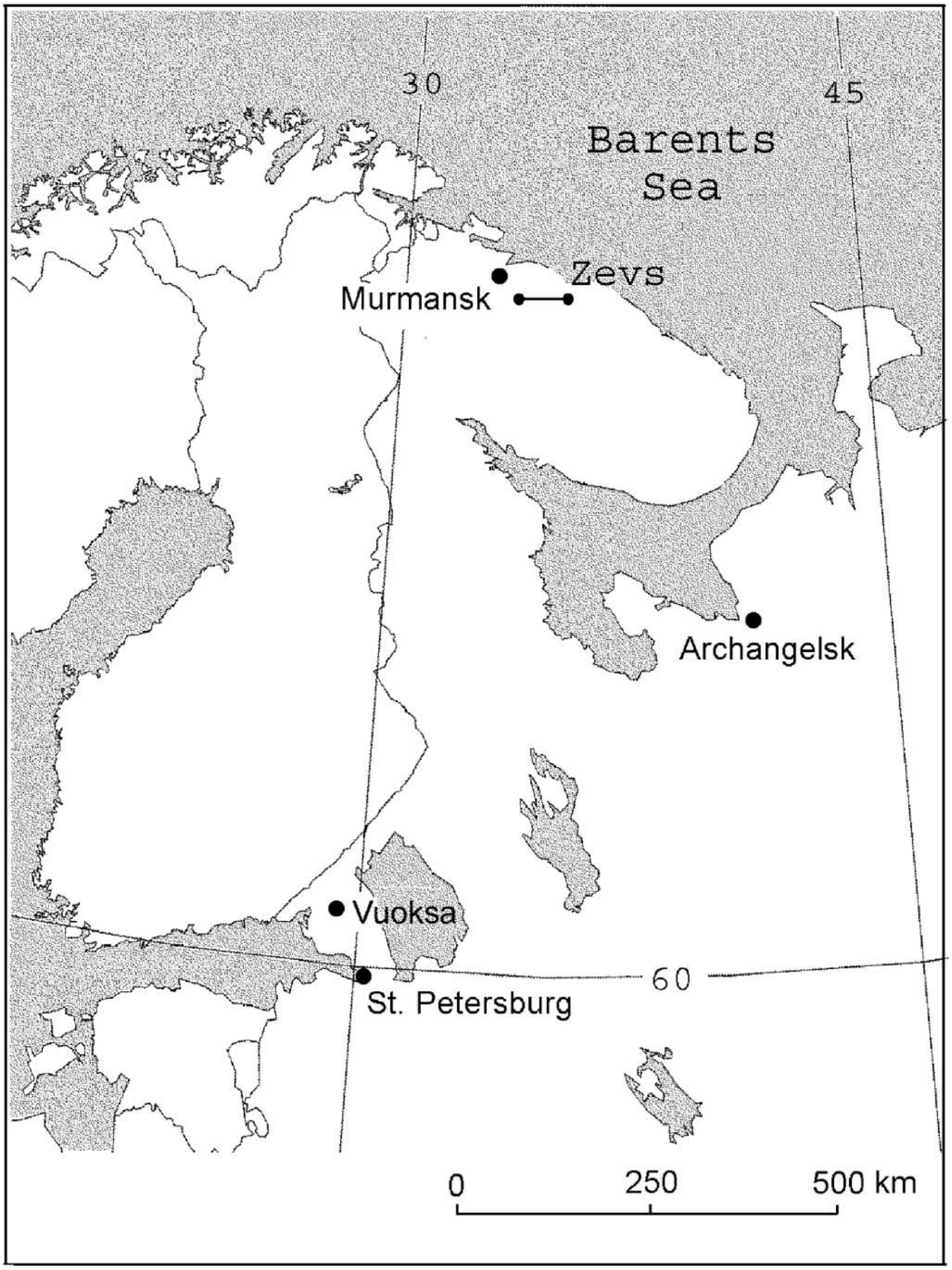

Fig. 1. Location of the ELF radio station “Zevs” and the test site “Vuoksa”.

harmonically varying electromagnetic fields of controlled sources.

There is a significant potential for seismic activity monitoring in the application of the extremely low frequency (ELF) radio station "Zevs". The advantage of the use of an artificial ELF signal for seismic activity monitoring in comparison with other methods of electromagnetic soundings (e.g., use of the MHD generator fields or the natural electromagnetic fields) is the stationary character of the source field. To obtain high accuracy and signal/noise ratio of measurements, any required duration of signal stack can be used. The theoretical fundamentals of the frequency sounding method for harmonically varying fields are well developed. The ELF station is a powerful source, and its electromagnetic fields can be measured in all seismically hazardous regions of Russia and in neighboring countries.

The ELF station "Zevs" is located in Kola Peninsula (Fig. 1). It consists of a generator of harmonically varying current and an antenna with a length of about 60 km, oriented in an E–W direction and grounded at the ends. The value of the current in the antenna reaches 300 A. The ELF station can radiate signals of extremely low frequencies in the range from tens to hundreds of hertz. Its signal can be measured up to about 10,000 km away.

The results of measurements of the ELF station electromagnetic fields for earthquake prediction are represented as an apparent electrical resistivity ρ_a, or the modulus and phase of the impedance Z, which is, at the surface, equal to the ratio of horizontal, orthogonal components of the electric and magnetic fields. The values of impedance modulus are related to apparent resistivity, for plane vertically incident waves, by $\rho_a = |Z|^2/\omega\mu_0$, where $\mu_0 = 4\pi \times 10^{-7}$ H/m — magnetic permeability of vacuum, $\omega = 2\pi f$—angular frequency, f— frequency (Hz). The use of the plane wave approximation can be confirmed for a particular region by the results of theoretical calculation (Saraev and Kostkin, 1997).

To assess the application of the ELF station to earthquake prediction the components of electromagnetic fields of the source have been measured and the data have been compared with deformations of the Earth's crust caused by the tidal phenomena. The aim was to study the factors determining the accuracy of measurements of the ELF-station fields.

2. Studies of the tidal phenomena relating to stress–strain state of medium

Connections between apparent resistivity changes and deformations of the medium caused by the tidal phenomena were studied earlier in Japan (Rikitake, 1976). An array of small size with distance between electrodes equal to 1.6 m was used with a variometer of the apparent resistivity. A compensatory method allowed a high accuracy of measurements (relative error was 10^{-5}). A connection between ρ_a anomalies and deformation of the medium caused by the tidal phenomena was found. The results of measurements were compared to deformation data. It was noted that a deformation of 10^{-6} caused by the tides was correlated with the relative ρ_a changes of about 10^{-4}.

Diurnal variations of apparent resistivity connected with the tides were registered in the seismically active region of Garm, Tadjikistan, using a direct current dipole array with a distance between transmitter and receiver of 7–8 km (Altgausen and Barsukov, 1970). The amplitude of ρ_a variation over 2 days varied from 4% to 10%. The periodicity coincided with horizontal deformations of the Earth crust obtained by measurements at a station, located 250 km away from the test site. The extremes of ρ_a curve were observed about 3–4 h later than that of the deformation curve. The authors explained the variations of apparent resistivity by variation of pressure and, accordingly, porosity of the rock owing to tides. They did not exclude the influence of possible oscillations of the ground water level. The lag of extremes on ρ_a curve compared to the deformation curve was explained by an inhomogeneous structure of the Earth crust near to the observation site.

A similar work was carried out at the Ashkhabad test site by a transient sounding method (Avagimov et al., 1988). The distance between the transmitter dipole and the receiving stations was 5–13 km. The measurements showed that the diurnal ρ_a variations were detected with a relative amplitude of 4.5–5.3%. Data about tidal deformations were obtained using a tilt meter. The comparison of ρ_a variations and declination of the Earth surface $\Delta\varphi$ showed a good correlation. The authors connected changes of ρ_a with the stress–strain state of medium.

Tidal deformation of the Earth arise from the influence of the gravitational attraction of the Moon and the Sun. It depends both on the static influence of the tidal forces, and from dynamic effects, arising from a series of factors (e.g., the elastic characteristics of the ground, the tides in the seas and oceans, the appearance of resonance) (Pariisky, 1963). The greatest tidal effect on the Earth is due to the Moon. The tidal influence of the Sun is about two times smaller. Tide forces act both on the surface, and inside the Earth, gradually decreasing to zero at its center.

3. Calculations of the Earth tides deformations

The observation site for the experimental measurements was on the Karelia isthmus. The test site "Vuoksa", where the measurements were carried out, is at a distance of 950 km from the ELF station (Fig. 1). The test site is located on the Vuoksa granodiorite massif among metamorphic rocks (gneiss, crystalline slates) of upper and middle Proterozoic age. The region is suitable for study of the ELF station electromagnetic fields and natural electromagnetic fields, as it is away from high-voltage and local transmission lines and is characterized by a low level of industrial noise.

Calculations of the Earth deformations caused by the tides in the region of the test site "Vuoksa" and comparison with the results of measurements of the ELF station electromagnetic field impedance have been carried out at the Institute of Applied Astronomy RAS. The calculations have been made using of the most up-to-date algorithm (Mathews et al., 1997), currently adopted as an international standard.

On a planetary scale, the analysis of the spectrum of tidal deformations shows that the semidiurnal and diurnal harmonics predominate. The maximum of horizontal displacement varies poorly with latitude and, on the average, is about 10 cm. The maximum of vertical displacement varies from about 60 cm at the Equator to 12 cm at the pole with cosine type a dependence.

The calculated deformation of the Earth at the test site "Vuoksa" for the vertical (ΔH), N–S (ΔN) and E–W (ΔE) directions for 2 days (26 and 27 June 1996) are shown in Fig. 2. The most noticeable amplitudes of deformations up to 20 cm are characteristic of the ΔH component. The maximum raising of the Earth surface was on 26 June at 06:45 (UT) and on 27 June at 07:30 (UT). The maximum lowering of the Earth surface was on 26 June at 22:45 and on 27 June at 23:15. Other components of the Earth surface displacement are smaller (ΔE of order 9 cm, and ΔN of order 6 cm). The extremes for various components of deformation do not appear simultaneously. The maximum value for ΔE is observed at about 04:00 and for ΔN about 7 h before the maximum of the ΔH curve.

4. Description of the ELF receiving equipment

Two- and four-channel modifications of the "apparatus of correlation functions" (ACF) manufactured at the Earth Crust Institute of St. Petersburg State University for use in audiomagnetotelluric (AMT) sounding have been used in the experiment. The signals of the horizontal components of the electric field have been measured using ACF instruments by grounded receiving lines with a length from 20 to 100 m. Horizontal components of magnetic fields were measured by induction magnetic antennae.

The analog part of the ACF device consists of amplifiers with stepwise switching of attenuation and capability of suppression of industrial frequency signals, that provide linear transformation of input signals with amplitude from 1 μV up to 0.3 V. A stack of auto correlation functions $K_{EE}(\tau)$ and $K_{HH}(\tau)$, connected with the horizontal components of the electric and magnetic fields, and also the mutual correlation function $K_{EH}(\tau)$ are calculated in digital format.

The power spectra $S_{EE}(f)$ and $S_{HH}(f)$ are found by Fourier transformations applied on correlation functions, and values of the surface impedance element Z_{xy} and apparent resistivity ρ_a have been determined. The phase of the impedance φ_z has been calculated from real and imaginary parts of mutual spectral density of signals $S_{EH}(f)$. For an evaluation of the non-coherent part of the investigated signals the values of a coherence coefficient $G_{EH}(f)$ are calculated. The coherence coefficient allows estimation of the reliability of the results.

Both a four-channel apparatus, ACF-4, and a two-channel apparatus, ACF-2.2, have been used in the experiment. The range of the ACF-4 operational frequencies was 1–3200 Hz, the width of frequency

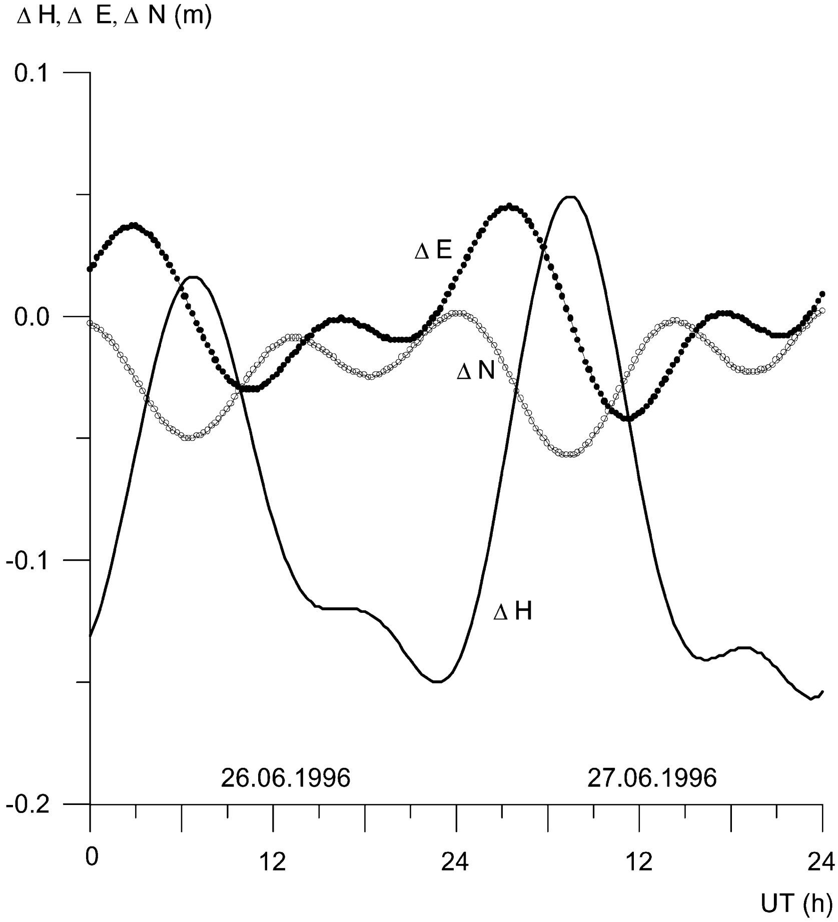

Fig. 2. Calculations of the Earth tidal deformations in vertical (ΔH), N–S (ΔN) and E–W (ΔE) directions.

sub ranges 200 Hz, and the frequency resolution was 0.66 Hz. At frequency sub ranges of 2 Hz; the frequency resolution of ACF-2.2 was 0.007 Hz. It has been used for measurements of the ELF-station signals, and the range of operational frequencies was 1–260 Hz. The apparatus provides a direct record of signals as well as the recording of correlation functions.

The narrow-band mode of measurements allows increased signal/noise ratio and a higher accuracy of measurement of the controlled source harmonically varying field signals. The spectral power density (SPD) of signals of the ELF-station magnetic field in wide-band and narrow-band modes are compared in Fig. 3. As is visible from the figure, in the wide-band mode the SPD of the ELF-station signal exceeds the level of the natural magnetic field by three times, whereas in the narrow-band mode the excess is 2 orders of magnitude higher.

5. Analysis of experimental results

Measurements using the ACF-4 device have been made for the study of the geoelectrical section of the observation site. The maximum and minimum amplitude $\rho_a(2)$, $\rho_a(1)$ and phase $\varphi_z(2)$, $\varphi_z(1)$ curves (Fig. 4) have been obtained for two main directions. The minimum $\rho_a(1)$ curve correspond to an magnetic azimuth of 80–90°, and the maximum $\rho_a(2)$—of 350–10° from North. As the ρ_a values of the two curves differ approximately by a factor of 2, some

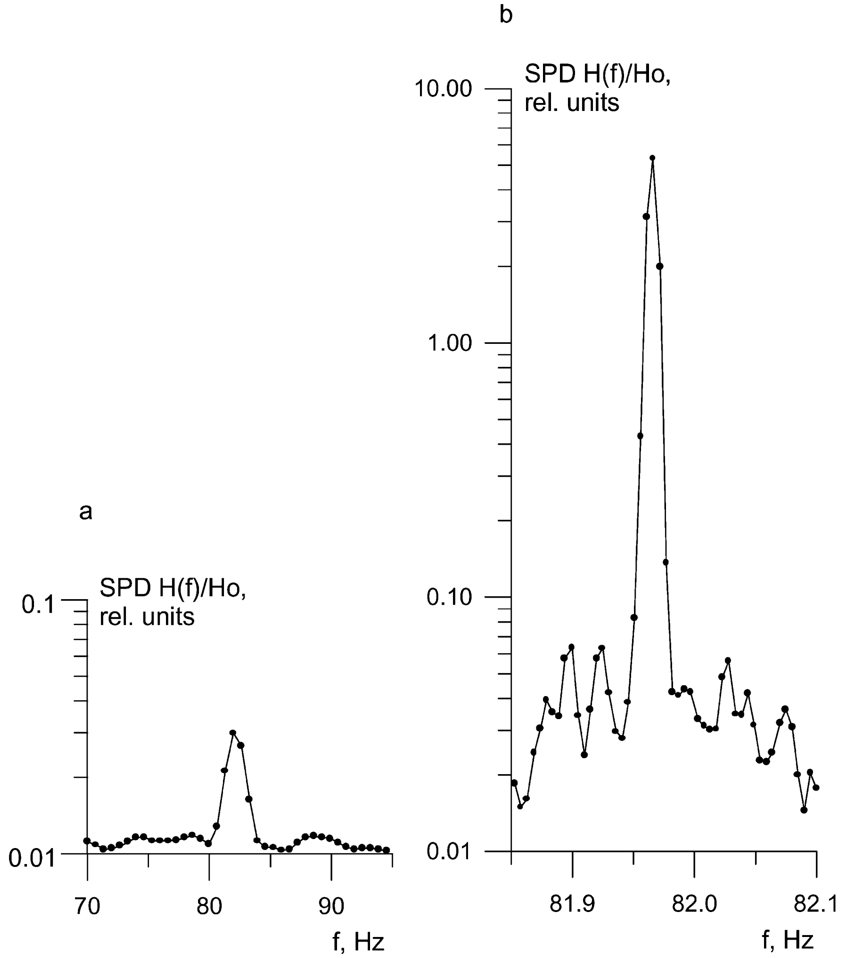

Fig. 3. Comparison of the ELF radio station signal with frequency resolution of 0.66 Hz (a) and 0.007 Hz (b).

non-uniformity of the geoelectrical section in the horizontal direction must be considered.

A 1-D inversion of effective values $\rho_a(\text{eff}) = \sqrt{\rho_a(1)\rho_a(2)}$ and $\varphi_z(\text{eff}) = (\varphi_z(1) + \varphi_z(2))/2$ curves has been made to give an estimation of the geoelectrical cross-section at the observation site. The following values of apparent resistivity and depths to the base of each layer describe the geoelectrical section:

$\rho_1 = 170\ \Omega$ m	$H_1 = 58$ m
$\rho_2 = 2200\ \Omega$ m	$H_2 = 1700$ m
$\rho_3 = 8000\ \Omega$ m	$H_3 = 9100$ m
$\rho_4 = 640\ \Omega$ m	

Measurements of the components of the ELF station electromagnetic field in the experiment have been also made using the ACF-2.2 device in the narrow-band mode. Before measurement the orientations of maximum signals of electric and magnetic field were determined by clockwise rotation of the measurement system. These directions corresponded to azimuths for the electrical receiving line of 120° and the magnetic antenna of 30° from North.

The ρ_a curve for the extremely low frequency sounding (ELFS) method using the ELF-station signals have been obtained for frequencies 41.6–166.6 Hz (Fig. 4). This curve lies between the minimum and maximum ρ_a curves determined by AMT and closer to

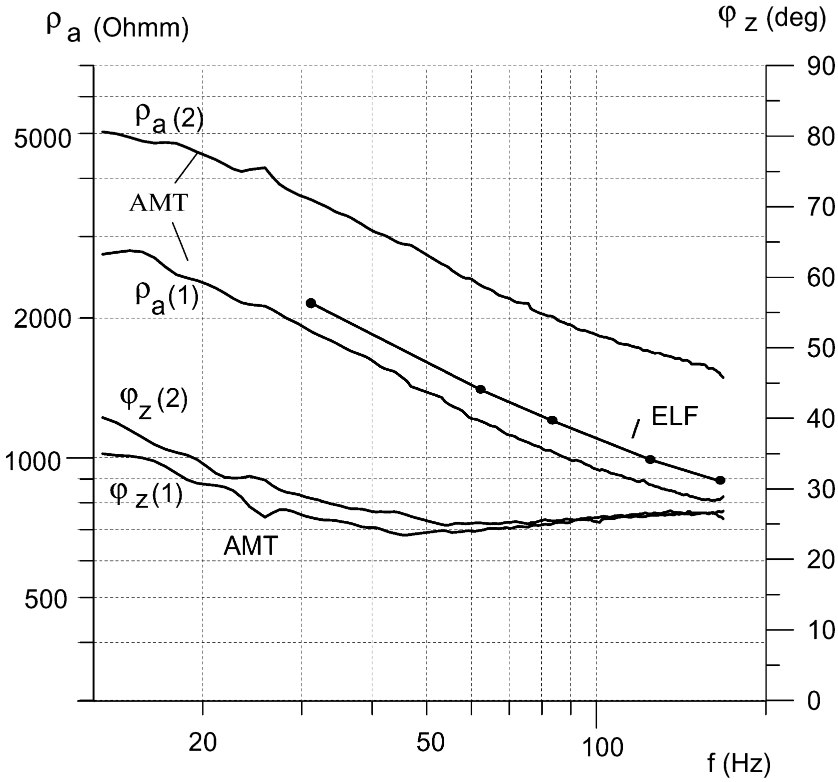

Fig. 4. Results of the audiomagnetotelluric (AMT) and extremely low frequency (ELF) soundings at the observation site.

the minimum $\rho_a(1)$ curve, which correspond to the magnetic azimuth of 80–90°. Such result for the ρ_a curve for the ELFS method, obtained with the direction of the receiving line of the electrical field with length 60 m at azimuth 120°, is in agreement with the northwest orientation of geological structures in this region.

To estimate the effects caused by the tidal phenomena, measurements of the ELF-station signals at frequency of 80 Hz from 05:00 (UT) on 26 June till 05:00 (UT) on 27 June 1996 have been made. Measurements are absent from 15:00 (UT) until 20:00 (UT) because the ELF station did not work that period. The receiving line of the electric field was 60 m in length, oriented at 120°, and magnetic antenna was oriented at 30° from North. The measurements have been carried out every 20 min, the ELF station working periods were 7 min.

The results of measurements of apparent resistivity using the artificial ELF field are shown in Fig. 5a, in comparison with the curve of calculated vertical deformations of the Earth ΔH. The correlation coefficient between ρ_a and ΔH is equal to 0.73.

In the same plot, a smoothed curve ρ_{as} is also presented. This has been computed from the observed data ρ_a using Whittaker's method (Malkin, 1996). As is visible from the figure, ρ_{as} has a higher degree of a correlation with the ΔH curve with correlation coefficient equal to 0.95.

Since the intention is to investigate the correlation between measured values of ρ_a and tidal deformation we are interested in the extraction from the observed values of signal in the frequency band corresponding to tidal effects. This can be achieved by filtering (or smoothing) of measured ρ_a to eliminate noise and high-frequency variations (which can interfere with low-frequency signal in statistical analysis) and retain only the signal in the frequency band above the 6-h period. We chose this value of frequency cutoff because two main components of tidal effect have

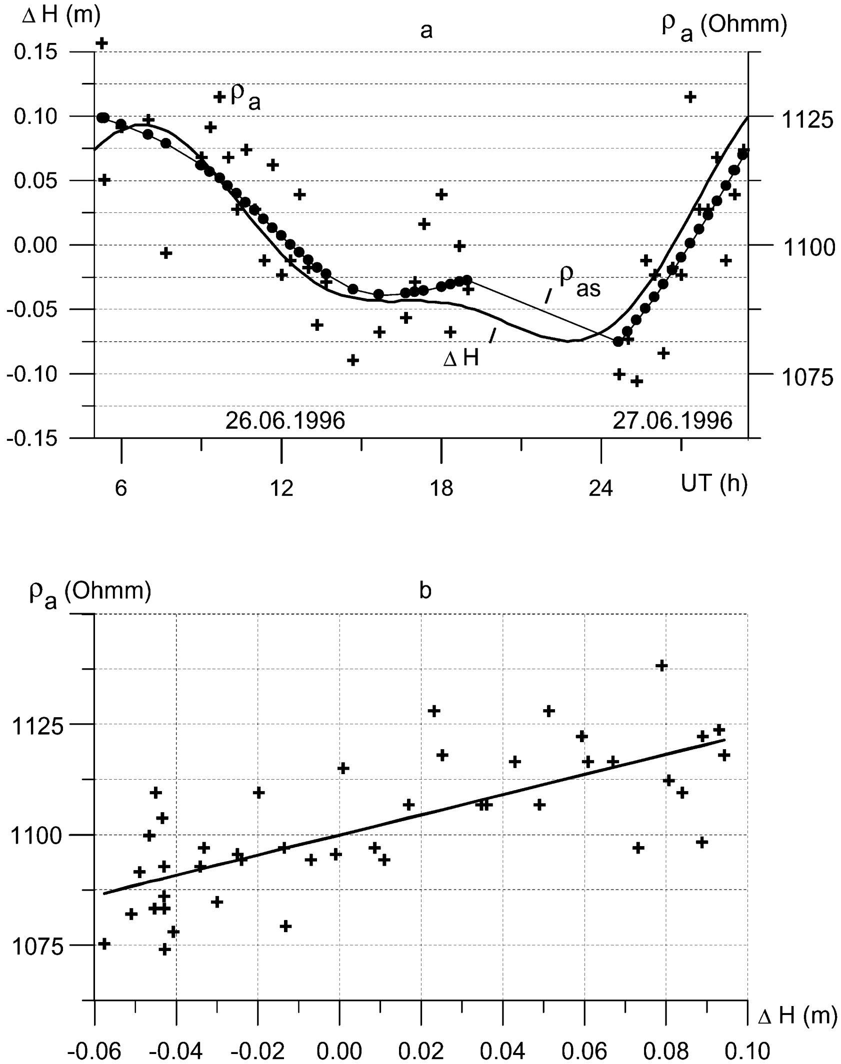

Fig. 5. (a) Comparison of changes of apparent resistivity ρ_a, smoothed apparent resistivity ρ_{as}, and vertical tidal deformation ΔH, (b) correlation plot between apparent resistivity ρ_a and vertical tidal deformation ΔH.

periods about 12 and 24 h. We used Whittaker's technique for smoothing the raw ρ_a and get a pure low-frequency signal for further comparison with tidal deformations.

Whittaker's method for smoothing of a time series minimizes the functional $Q=\varepsilon F+S$, where ε is the parameter defining the degree of smoothing, $F=\sum p_i(y_i-y_i^*)^2$, $S=\sum(\Delta^3 y_i)^2$, y_i—observed values, Δ^3—their 3-order differences, p_i—weights of observed values, y_i^*—smoothed values, $i=1,\ldots,n$. Here, F reflects fidelity of the smoothed curve to the observed values, and S is the smoothness of the of the curve. These formulae correspond to equally spaced data. Those for unequally spaced data can be found in (Malkin, 1996). The resolution of the problem requires the solution of a system of n linear equations with a coefficient matrix of band structure with seven co-diagonals.

Whittaker's method provides flexible adjustment of the degree of smoothing and hence transfer function. It can be also used as a frequency filter when applied twice with different values of ε. This method gives, in principle, similar results to the more widely used smoothing spline or Gaussian smoothing technique, but provides better frequency cutoff.

To obtain a more detailed relationship between apparent resistivity ρ_a and ΔH tidal variation, a linear regression analysis has been performed. The numerical expression connecting ρ_a and ΔH has been computed by the least squares method. The following dependence was found: $\rho_a = 1097 + 418\Delta H$, where ΔH is scaled in meters and ρ_a in Ω m. Fig. 5b shows the regression line along with the measured values of ρ_a.

The uncertainty in ρ_a measurements is estimated on the basis of the mean quadratic deviation of isolated points of ρ_a from the ρ_{as} curve. This is estimated to be $\pm 0.6\%$.

The ρ_a changes in 24 h of the experimental data was 7%. The values are close to the values of variations observed at Garm (Altgausen and Barsukov, 1970) and at Ashkhabad (Avagimov et al., 1988) test sites. The results of this experiment and data of previous studies indicate that significant ρ_a variations are connected with tidal phenomena. These variations are of the same order of magnitude as expected ρ_a changes before earthquakes. As noted above, the amplitude of maximum vertical tidal displacement increases from the Pole to the Equator. Therefore, further to the South ρ_a variations connected with the tidal phenomena should be expected to be larger.

To increase the reliability of the earthquake prediction it is necessary to take into account the influence of the tides at seismic monitoring sites where observations of ρ_a variations are made and to carry out appropriate correction of the data. The values of ρ_a tidal changes can be precisely defined from calculations of the Earth surface deformations using correlation equations between ρ_a and ΔH similar to that obtained for the test site on the Karelia isthmus.

The comparison of ρ_a and ΔH curves (Fig. 5) shows that the increase of apparent resistivity corresponds to raising of the Earth surface and the ρ_a decrease corresponds to lowering. It is possible to explain such a characteristic of the change in ρ_a by the so-called "sponge effect" (Melchior, 1966). At compression, the water penetrates into small-sized cracks, pores and capillary tubes of a rock, forming a net of interconnected films and channels. On reduction of pressure, the water outflows from small-sized cracks, pores and capillary tubes and the form of the fluid distribution in rock gains a less connected character. The resistivity of rocks mainly varies due to the change of character of the fluid distribution in the pore space. It is lowered due to a greater degree of connection of water during compression, and is increased due to less connection as a result of tension of the medium.

Experimental measurements with the use of the ELF station make possible further conclusions. The ground water oscillations near the Earth surface could be the main factor in water saturation cycles of rocks to rather large depth due to fluid penetration in small-sized cracks and pores under the tidal phenomena. The depth of investigation is about 1000–1500 m at a frequency of 80 Hz for the calculated parameters of the geoelectrical section. Under these conditions it is possible to expect contribution to ρ_a variations from deep horizons of the geoelectrical section, much deeper than the ground water level.

This manner of rock ρ variation due to the change of stress–strain state under the effect of the tides agrees with laboratory results of measurements on samples with a small amount of water (igneous rocks or dense sedimentary rocks) (Parkhomenko, 1965). If the water saturation of rocks is more intensive (such as in friable sedimentary rocks or fractured igneous rocks) the opposite of this phenomenon can be observed: on compression of the samples an increase of ρ is observed. In this case the water distribution in the rocks has an interconnected character, and after pressure increases, a discontinuity in the net of films and channels takes place.

6. Conclusions

Based upon the above investigation, it is possible to make the following conclusions.

1. The results of previous research on correlation of tidal phenomena and variation of apparent resistivity at earthquake prediction sites are analyzed in the paper. It is noted that the tidal phenomena were used earlier in the development of the methods of electromagnetic monitoring of the stress–strain state of the geological media.

2. The calculations of the tidal deformations of the Earth's crust at the site of experimental work on the

Karelian isthmus show that the most significant amplitude of displacement (20 cm) is in the vertical direction. Horizontal deformations are less noticeable (6–9 cm), and their maxima are shifted in time compared to vertical deformation. Diurnal variations of apparent resistivity of about 7% are detected using the ELF station "Zevs" and receiving hardware-program complex ACF-2.2. These variations are connected with deformation of the Earth's crust caused by the tidal phenomena.

3. To increase the reliability of earthquake prediction, it is necessary to take into account the influence of tidal effects, the values of which are comparable to ρ_a changes before the onset of earthquakes. The ρ_a variation caused by the tide phenomena can be predicted with the use of appropriate equations of correlation relationships, which may be obtained from experimental work and calculations of the Earth's surface deformations.

4. A high degree of correlation of apparent resistivity values, observed from measurements of the ELF station electromagnetic field impedance and vertical deformations of the Earth surface caused by the tides phenomena, were shown. The correlation coefficient between smoothed ρ_{as} values and ΔH deformations is 0.95. The observable variations of the impedance and ρ_a are connected with the changes of electrical resistivity of rocks and are explained by the "sponge effect". A decrease of ρ_a occurs on the compression of the Earth's crust during outflow and the influx of waters in to small-sized pores, cracks and capillary tubes of rock with the derivation of a network of interconnected films and channels. A ρ_a increase takes place on tension of the Earth's crust during the inflow and the outflow of fluids from small-sized pores, cracks and capillary tubes, because of fluid distribution has a smaller degree of interconnection.

5. A rather high accuracy is realized for measurements of the ELF station electromagnetic field impedance. The uncertainty in apparent resistivity determination from experimental measurements has a variation value of $\pm 0.6\%$. This allowed identification of a diurnal ρ_a change of 7%.

6. Analysis of the potential use of ELF station "Zevs" for the study of the stress–strain state of geological media and experimental results show that effective systems of earthquake prediction in seismically hazardous regions of Russia and neighboring countries using the receiving hardware–software complexes ACF-2.2 can be created.

Acknowledgements

This investigation was performed with the financial support of the "Integration" program. We thank Malcolm Ingham for his help in the preparation of the manuscript.

References

Altgausen, N.M., Barsukov, O.M., 1970. About time variations of electroconductivity. The Physical Basis of Searches in Methods of Prognosis of Earthquakes. Nauka, Moscow, pp. 104–110, in Russian.

Avagimov, A.A., Ataev, A.I., Ataev, S.A., et al., 1988. Connection of anomalous measurements of electric resistivity of rocks in a fracture zone with tides deformations of the earth crust. Izv. Akad. Nauk Turkm., SSR, Ser. Fiz.-Tekh., Khim. Geol. Nauk 5, 50–52, in Russian.

Barsukov, O.M., 1973. Variations of electric resistivity of mountain rocks connected with tectonic causes. Tectonophysics 14, 273.

Malkin, Z.M., 1996. On the smoothing by Whittaker's method. Kinematika Fiz. Nebesnykh Tel 12, 71–74.

Mathews, P.M., Dehant, V., Gibson, J.M., 1997. Tidal Station Displacements. J. Geophys. Res. 102 (139), 20469–20477.

Melchior, P., 1966. The Earth Tides. Pergamon, 482 pp.

Pariisky, N.N., 1963. Earth tides and internal structure of the earth. Izv. Akad. Nauk., USSR, Geophys. Ser. 2, 193–215, in Russian.

Parkhomenko, E.I., 1965. Electrical Properties of Rocks. Nauka, Moscow, 164 pp., in Russian.

Rikitake, T., 1976. Earthquake Prediction. Elsevier, Amsterdam, 388 pp.

Saraev, A.K., Kostkin, P.M., 1997. Structure of ELF radio station electromagnetic field. Abstract of Comm. of Russian–German seminar. Moscow, March 11–15, 29.

Stopinski, W., Teisseyre, R., 1977. Precursory rock resistivity variations related to mining tremors. Acta Geophys. Pol. 30 (4), 293–320.