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Monitoring of tidal variations of apparent resistivity

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ABSTRACT

Possibilities of using tidal phenomena for the development of a monitoring technique of apparent resistivity (ρ_a) variation registration, and the analysis of previous studies, are considered in this paper. The properties of tidal deformation of the Earth's crust are analyzed. The high accuracy of ρ_a measurements (not more than 1% error) using modern audiomagnetotelluric (AMT) instruments allows measurement of small changes in the apparent resistivity (2-3 %). The results of AMT monitoring in different geological settings show a good correlation between ρ_a variations with amplitudes of 3-8 % and variations of the vertical tidal deformations, dH. Tidal ρ_a variations are easily observed in heterogeneous geological environments, but they are not observed at sites with a thick homogeneous sedimentary cover. Both direct and inverse correlations between ρ_a and dH plots were observed, which can be explained by the dependence of the degree of water saturation in the rocks: direct correlations between ρ_a and dH appear in dry rocks with high resistivity and inverse correlations are observed in water saturated rocks with low resistivity. As a result of the monitoring performed at a site with anisotropic rocks, an inverse correlation for E-polarization and a direct correlation for B-polarization were observed. These results show that the AMT sounding method can be applied to the monitoring of the stress-strain state of rocks prior to earthquakes.

KEYWORDS **Audiomagnetotelluric monitoring. Apparent resistivity. Tidal variation.**

INTRODUCTION

Electromagnetic monitoring of the stress-strain state of rocks and geodynamic processes is based on the observation of different seismic electrical phenomena. There is considerable experience in transient variation measurements of the Earth's electric field, called Seismic Electric Signals (SES). These precursors were detected in Greece by the VAN network prior to earthquakes (Varotsos et al., 1988). The origin of SES phenomena has been investigated by laboratory experiments (Hadjicontis and Mavromatou, 1994). Recordings of short-term earthquake precursors and electromagnetic emission in the VLF range have been obtained by Eftaxias et al. (2001).

Electromagnetic monitoring based on measurements of electrical resistivity (ρ) variations is widely used for the control of the rocks stress-strain state. There exists a high sensitivity of ρ to the structural features of rocks, water content and mineralization. When the geological medium is deformed under the effect of external pressure, its pore sizes vary, fluid motion occurs and hence the rock resistivity changes (Rikitake, 1976).

The application of electromagnetic (EM) sounding methods for monitoring of rock stress-strain state is based on the study of the temporal evolution of the most frequently measured parameter - the apparent resistivity (ρ_a). EM soundings are widely used for monitoring in China, Japan and other countries. The results of the measurements show that ρ_a changes were usually observed during a period of several months before an earthquake (Barsukov, 1972), and the amplitudes of these variations can be up to 10–20% (Rikitake, 1976). Lu et al. (1999) analyzed the results from 20-years of monitoring and show ρ_a anomalies before the Tangshan Earthquake (1976) in China. There are examples of successful earthquake predictions using such data, e.g., the Haichen Earthquake in China, 1975 (Gere and Shah, 1984). The testing of new methods and the development of measurement and data processing techniques are the necessary conditions for the increase in reliability of earthquake prediction using ρ_a variations as the precursor of an earthquake.

Because earthquakes are episodic, it is rather difficult to study the regularities of the ρ_a variations before them. Therefore, we approach the modeling of earthquake situation processes based on the regular observations of ρ_a tidal variations. Changes of the rock stress-strain state due to the tidal effect are similar to rock deformation processes before an earthquake, and therefore observations of ρ_a tidal variations can be applied to the study of the seismo-electromagnetic phenomena before earthquakes. The modeling focuses on the study of rock property changes in situ and repeated experiments can be carried out because of the regularity of tides.

Earlier studies of ρ_a variations caused by tidal deformations in the Earth's crust were applied to rock stress-strain state monitoring using controlled source electromagnetic fields (Altgausen and Barsukov, 1970; Rikitake, 1976; Avagimov et al., 1988). It was found that the daily ρ_a changes connected with Earth tides were up to 4-10 %. The experiments with the Russian ELF transmitter (Saraev et al., 2002; Kononov and Zhamaletdinov, 2002) have shown ρ_a diurnal changes by up to 7-15 % due to tidal phenomena.

In order to use ρ_a variations for earthquake prediction monitoring, networks should be created using high-accuracy methods. The applied methods should have an investigation depth high enough to account for rock resistivity changes due to the influence of seasonal and meteorological factors.

The audiomagnetotelluric (AMT) sounding method meets all these requirements. It has not been widely applied before in seismic activity monitoring because of the measurements' low accuracy due to source instability of natural EM fields and the influence of industrial noise in the audio frequency range.

In recent years, the accuracy of the AMT method has increased. In favorable noise conditions, new AMT instruments permit obtaining data with an acceptable quality level for rock stress-strain state monitoring, confirmed by its use for measurements of small tidal variations of the apparent resistivity.

The results of such tidal observations can be used during the study of rock resistivity changes before earthquakes to select sensitive zones for the receiving devices subsequent installation, to choose the optimum frequencies for monitoring in intervals of geoelectric cross-sections with the best stress-strain sensitivity, and finally to take into account tidal effects as a hindering factor for seismic activity monitoring. Moreover, when measuring with modern high accuracy instruments, it is necessary to take into consideration ρ_a tidal variations not only during monitoring observations, but also during the application of EM sounding methods for solution, geological problems solution.

In this paper, we study the apparent resistivity tidal variations using the measured data of the natural electromagnetic field in the audio frequency range.

TIDAL DEFORMATIONS OF THE EARTH'S CRUST

The gravitational attraction of the Moon and the Sun produces tidal deformations of the Earth and changes of the rock stress-strain state. Tidal forces have their maximum value on the Earth's surface, decreasing in depth, and at the centre of the Earth they can be neglected. The largest deformations are observed in the vertical component dH, where the peak-to-peak deformation varies from about 12 cm at the Poles up to about 55 cm at the Equator. In the N-S (dN) and E-W (dE) directions, tidal deformations are smaller and in both cases the peak-to-peak deformation is about 10-12 cm for all latitudes. The main tidal influence is produced by the Moon; the amplitude of solar tide being approximately its half.

Earth's tidal deformation representations consist of some harmonic components with different periods and amplitudes. The tidal deformation spectral structure (main waves) is shown in Fig. 1. The largest tidal component is the lunar principal wave M2 with a period of 12.42 hours (half lunar day). The second largest amplitude is the wave K1 with a period of 23.93 hours (one sidereal day), which results from a combined influence of the Moon and the Sun. Other important components are the solar principal wave (or S2 wave) with a period of 12 hours, and the lunar principal diurnal wave (or O1 wave) with a period of 25.82 hours. Semidiurnal waves with periods of about 12 hours are primarily considered to be a result of the Earth's rotation. The diurnal waves with a period of about 24 hours are primarily explained by the inclination of the Moon orbit around the Earth and the Earth orbit around the Sun to the Earth Equator. The combined action of the Moon and the Sun and their relative movements produce a complex picture of tidal deformations. We may note that the deformation values and behaviors differ daily, monthly and annually. The minimum tidal deformation occurs during quadrature (when the position of the Moon is 90° from the Sun as observed from the Earth) and the maximum during syzygy (when the Sun, the Moon and the Earth are aligned) (Fig. 2A, B).

The syzygial and quadrature positions are determined by the Moon orbit around the Earth, and are repeated twice a month, i.e., within a month two syzygies and two quadratures are observed (Fig. 2C). The amplitude of the tidal deformations also depends on the varying distance between the Earth and the Moon: at apogee the distance is 406,000 km, and at perigee 354,000 km. Besides the semi-day and semi-month periodicity, semi-annual periodicity exists. It is related to the orbit of the Earth around the Sun and appears appreciably on the dH plots (Fig. 2D).

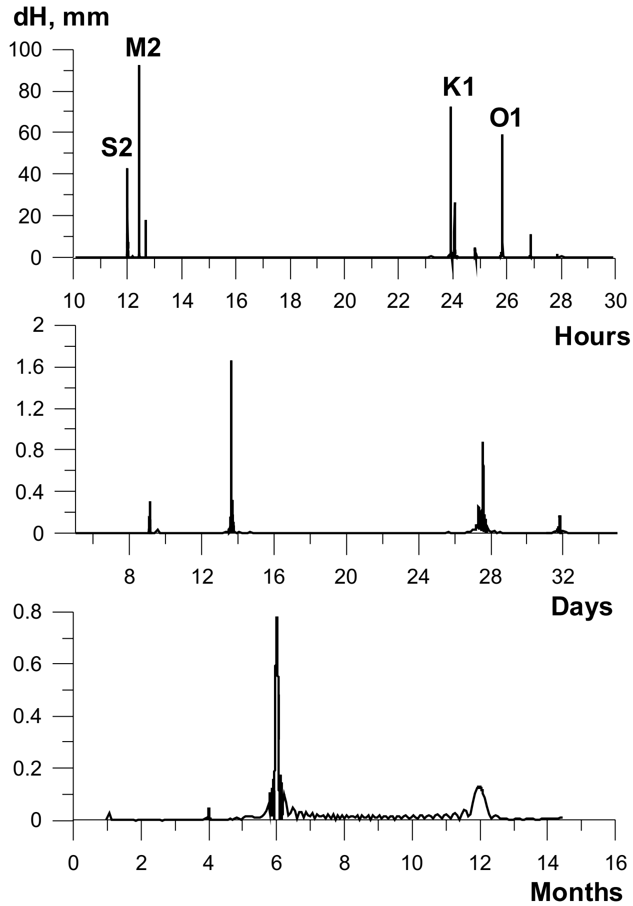

FIGURE 1 | **Harmonics of vertical tidal deformations for hourly, daily and monthly periods.**

The tidal dH deformations have been calculated using the algorithm of Mathews et al. (1997). These values are used for comparison with apparent resistivity changes in the experiments presented in this paper.

THE AMT METHOD AND EQUIPMENT

The AMT method is a high-frequency modification of the magnetotelluric (MT) method (Vozoff, 1991). It is based on natural electromagnetic field measurements in the frequency range from 1 Hz to 1 kHz (Strangway et al., 1973). The sources of these fields are distant thunderstorms. The model of the primary field as a plane wave is used for the AMT data interpretation.

The AMT data spectral decomposition allows us to obtain the frequency dependences of surface impedance (apparent resistivity, ρ_a) and impedance phase, φ_z. The depth of investigation depends on the signal frequency and rock resistivity at the measurement point.

Our experiments were based on the four-channel (tensor) ACF instrument implementation. The last version - the ACF-4M system - was created by Saint Petersburg State University and MicroKOR Ltd. (Saraev et al., 2003). The frequency range of the ACF-4M system is 0.1-800 Hz. It is divided into three sub-ranges 0.1-40 Hz (D1), 1-400 Hz (D2) and 1-800 Hz (D3). Thus, the input signal sampling frequencies are 160, 1600 and 3200 Hz, respectively.

The system consists of two horizontal induction coil sensors to measure the magnetic field components H_x and H_y, two grounded electric lines for measuring the electric field components E_x and E_y and the four channel recorder with 24-bit analog-to-digital converters. The storage of recording signals is carried out in the internal flash-memory (512 Mb) of the recorder. The recorder can be operated without use of an external computer. The equipment can be programmed to perform cyclic measurements, the beginning and end of which are synchronized using the GPS receiver. The mode of cyclic measurements is convenient for the monitoring of apparent resistivity and phase changes.

The equipment software consists of programs for measurement control, data processing with calculation of frequency dependences of apparent resistivity and phase and 1D and 2D inversion. The primary data (time series) are

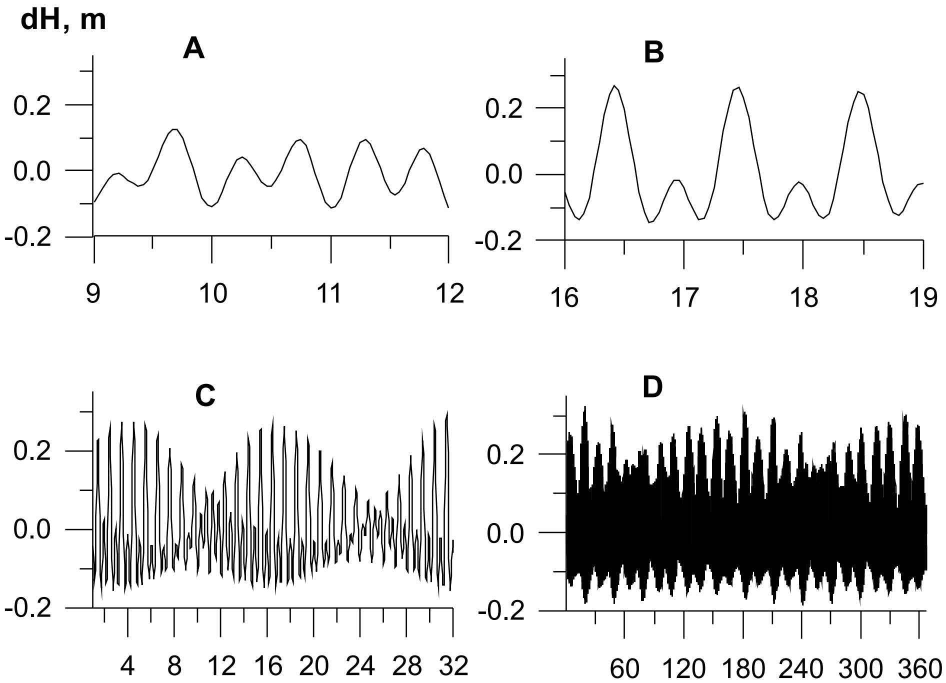

FIGURE 2 | **Features of the vertical component dH for tidal deformations for A) quadrature and B) syzigy positions of the Sun and the Moon and dH C) months changes and D) years changes. Horizontal axes in days.**

usually split into segments of 2048 or 4096 points length, at which point the fast Fourier transform is applied. Apparent resistivity and phase curves are obtained from the auto- and cross-spectra. Coherency values are used to estimate measurement quality. Robust procedures are applied at the sites with a high level of industrial noise. The ACF-4M system ensures high measurement accuracy (1-2 % for apparent resistivity and 0.5-1 degrees for phase).

DATA

The monitoring experiments for study of the temporal variation of apparent resistivity have been carried out in different regions of Russia and Kyrgyzstan using ACF systems. The monitoring data were analyzed in the frequency range of 7-400 Hz, in which the most reliable measurements by the AMT method are provided. For the frequency range of 0.5-6 Hz, appreciable changes in the primary field polarization within one day were observed which makes the interpretation of the monitoring results less reliable. For frequencies higher than 400 Hz, the data do not have good enough quality for monitoring due to the low level of the natural electromagnetic field.

Krasnoyarsk region

The simplified geological section of the site in the Krasnoyarsk region shows a 240 m thick upper layer with water saturated sands and clays and a lower layer granite basement. AMT sounding curves of the apparent resistivity (ρ_{a1}, ρ_{a2}) and phase (φ_{z1}, φ_{z2}) for two principal directions of the impedance tensor at this site are shown in Fig. 3 (orientation of the measuring array is determined by the direction

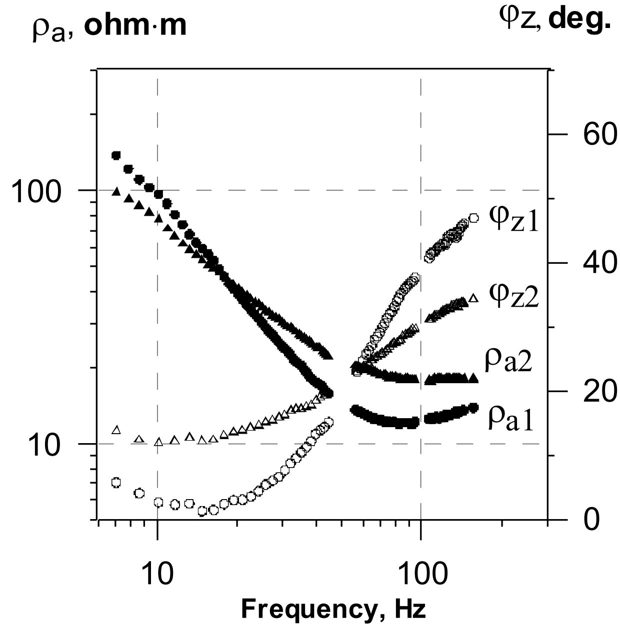

FIGURE 3 | **AMT sounding curves at the site in Krasnoyarsk region.**

of the receiving electric line). For this sounding, azimuthal directions 1 and 2 correspond to 60 and 140 degrees clockwise from the North, respectively. The principal directions which correspond to the maximum and minimum curves of the apparent resistivity are not perpendicular. This indicates some heterogeneity of the geological environment at this site. The low values of the phases are explained by the very resistive basement (more than 10000 ohm·m). We clearly observe convergences for both apparent resistivity and phase curves at high and low frequencies. Such features may indicate the evidence of heterogeneities in both the shallow and deep parts of the subsurface. The ρ_a values at the site vary from 20 to 100 ohm·m.

Whittaker's technique was applied to smooth the raw ρ_a values for the examples presented in the paper. It allows us to obtain a pure low-frequency signal which can be compared with tidal deformations (Malkin, 1996; Saraev et al., 2002).

The inverse dH and ρ_a plots correlation is observed according to the monitoring results at the frequency 130 Hz (Fig. 4). Such behavior was also observed for other frequencies from the range 7-200 Hz. The rise of the Earth surface corresponds to the apparent resistivity decrease which is observed for both ρ_{a1} and ρ_{a2} values. The ρ_a variations of about 8 % correspond to dH changes up to 30 cm.

The Tash Bashat site (Bishkek region)

At the Tash Bashat site, the simplified geological section is represented by a sedimentary cover with some heterogeneity and a granodioritic basement at 10 m depth. The curves of apparent resistivity for the azimuths 0 degrees (ρ_{a2}) and 90 degrees (ρ_{a1}) differ by a factor of 2 for frequencies higher than 100 Hz (Fig. 5a). In the low frequencies (less than 10 Hz) the ρ_a curves cross. The phase curves for frequencies higher than 100 Hz are close for both directions, and they diverge when the frequency decreases. Such curve features as in Fig. 5 (as at the test site in the Krasnoyarsk region) are evidence of heterogeneity in both the shallower and deeper parts of the cross section. The ρ_a values at this site vary from 200 to 600 ohm·m.

The monitoring results at the Tash Bashat site for the 7 Hz frequency show a direct dH correlation between both ρ_{a1} and ρ_{a2} plots (Fig. 6). The same behavior has also been observed for other frequencies (7-400 Hz) at this site. The 2-3 % ρ_a variations in Fig. 6 correspond to the dH changes up to 30 cm. At 12:00 -14:00 universal time (UT) or 17:00 – 19:00 local time, some differences (approximately 1%) appear in the ρ_a and dH behavior. We hope to find the reason for these differences in further studies.

The Karelia isthmus

A more complicated dependence was observed at the site with anisotropic rocks. The Vuoksa granodiorite mas-

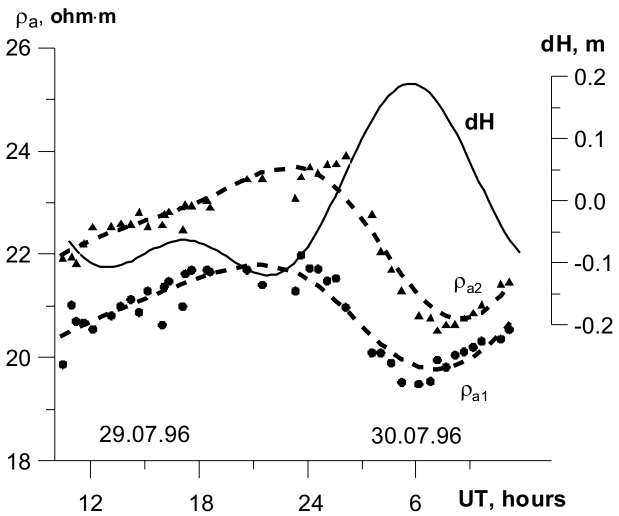

FIGURE 4 | **Monitoring results for the 130 Hz frequency (Krasnoyarsk region). Dotted lines are smoothed apparent resistivity plots.**

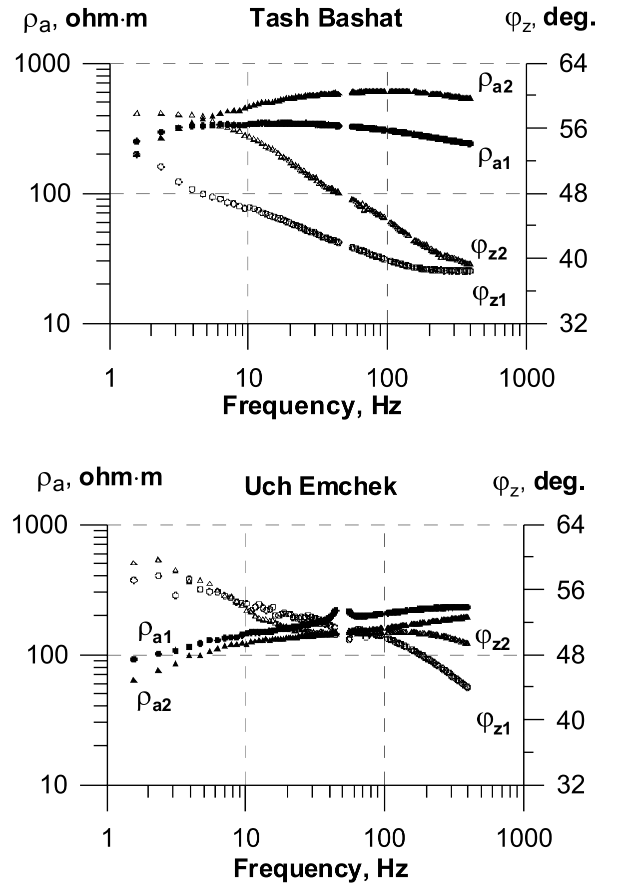

FIGURE 5 | **AMT sounding curves at the Tash Bashat and Uch Emchek sites in the Bishkek region.**

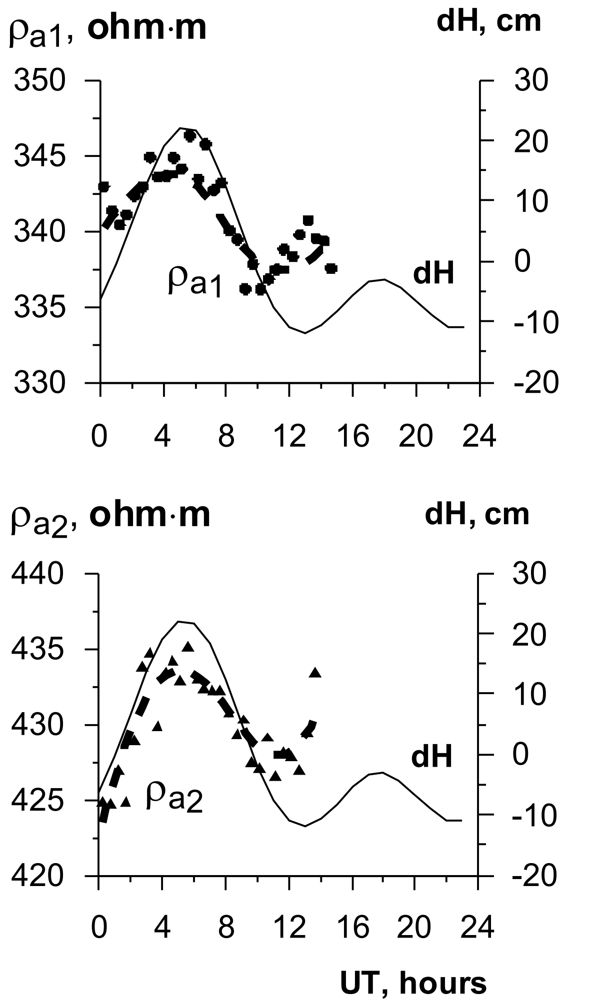

FIGURE 6 | **Monitoring results at the Tash Bashat site (4.06.2005) in the Bishkek region for the 7 Hz frequency. Dotted lines are smoothed apparent resistivity plots.**

sif on the Karelia isthmus is located among metamorphic rocks (gneiss, crystalline slates). The granodiorites are covered with sedimentary rocks having up to 30-40 m thicknesses. There is a weathered zone with thickness ranging from 10 to 40 m in the granodiorites upper part.

Fig. 7 shows the AMT apparent resistivity (ρ_{a1}, ρ_{a2}) and phase (φ_{z1}, φ_{z2}) curves for the impedance tensor principal directions at this site. The ρ_a values vary from 1000 to 5000 ohm·m. The minimum ρ_{a1} curve corresponds to the 80-90 degrees azimuth which coincides with the direction of geological structures (main faults, anisotropy of rocks) at this site (E-polarization). The maximum ρ_{a2} curve for the 350-10 degrees azimuth is directed across the geological structures (B-polarization). Some non-uniformity of the geoelectric section in horizontal direction is confirmed by ρ_a curve changes by a factor of approximately 2. AMT soundings previously acquired in this area show a constant influence from geological structures in the N-W direction on the behavior of the natural EM fields. Such a difference of ρ_a curves is typical for the area. The principal directions are not perpendicular, indicating some geological environment heterogeneity at the site.

The monitoring results are shown in Fig. 8 as plots of ρ_{a2} and ρ_{a1} for the frequencies of 70, 90 and 130 Hz in comparison with a dH plot. The dH maximum amplitude is about 0.15 m. The ρ_{a2} and ρ_{a1} plots' behavior shows that the most significant tidal variations (approximately 5 %) are characteristic of the minimum ρ_{a1} plot and low frequencies. For the frequencies of 70 and 90 Hz, an inverse correlation between the ρ_{a1} and dH plots and a direct correlation between the ρ_{a2} and dH ones are observed. For the frequency of 130 Hz, tidal variations are marked only for the minimum ρ_{a1} plot. The maximum ρ_{a2} plot has no correlation with the dH one. For higher frequencies, ρ_{a2} provides a small depth of investigation. Thus, for water saturated overlying rocks ρ_{a2} tidal variations are not observed.

The Uch Emchek site (Bishkek region)

The absence of tidal ρ_a variations in homogeneous sedimentary environments is illustrated by AMT monitoring data at the Uch Emchek site. At this site with a thick sedimentary cover (hundreds of meters) in the geological section upper part, low ρ_a values (70-200 ohm·m) were obtained. Curves of ρ_a and φ_z for 0 degree and 90 degree directions are close one to another (Fig. 5b). This indicates geological environment homogeneity.

A comparison of monitoring results at the Tash Bashat and Uch Emchek sites for the frequencies of 7, 70 and 175 Hz are presented in Fig. 9. At the Tash Bashat site with high stress-strain sensitivity, there are noticeable ρ_a changes; while at the Uch Emchek site with low stress-strain sensitivity, it can be seen that the dH changes up to 35 cm do not produce any ρ_a variation during the day. The absence of ρ_a changes at the Uch Emchek site is characteristic for both 0 degree and 90 degree directions.

The monitoring data in Fig. 9 also illustrate the high accuracy of the apparent resistivity measurements using the modern AMT instrument (not worse than 1%) and the possibility of measuring small (2-3 %) ρ_a changes. Hence, the AMT sounding method can be applied successfully to rock stress-strain state monitoring and earthquake prediction.

DISCUSSION

During the experiments, the ρ_a tidal variations were observed in heterogeneous geological environments. At sites with a thick homogeneous sedimentary cover, apparent resistivity variations were not observed.

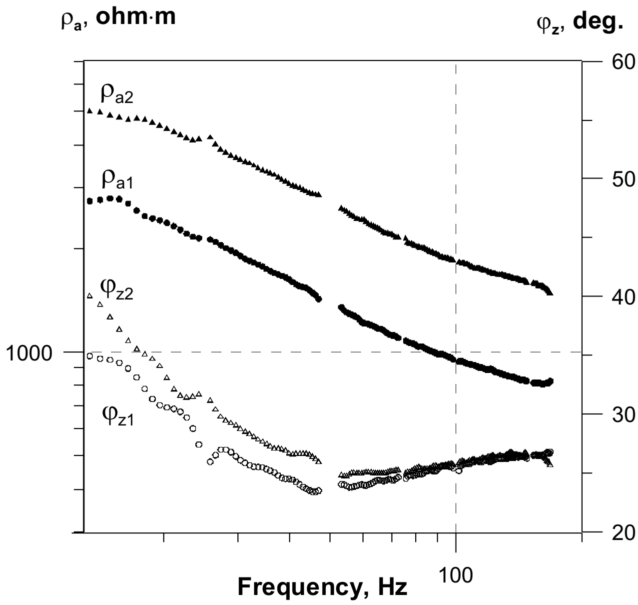

FIGURE 7 | **AMT sounding curves at the site on the Karelia isthmus.**

The correlation between the ρ_a and dH plots for sites in Krasnoyarsk and Bishkek regions can be explained by the degree of ground water saturation. When water fills a pore space completely, a rock has low resistivity. The compression of the medium (lowering of the Earth's surface) leads to the closure of the conductive water-filled channels, therefore increasing rock resistivity. Pressure reduction (associated with the rising of the Earth's surface) leads to a rock resistivity decrease. In this case, we observe an inverse correlation of the ρ_a and dH plots.

When there is low water content, a rock usually has high resistivity. In this case, the water distribution in the rock is disconnected. In a compressive regime, water penetrates into the pores and cracks, forming a network of interconnected channels. At the onset, reduction of pressure water outflows from the pores and has a less connected distribution. In this case, the so-called "sponge effect" appears (Melchior, 1966). During the monitoring, we observe the direct correlation of ρ_a and dH plots. Similar dependences were obtained during laboratory experiments with water-filled and dry specimens of rocks (Parkhomenko, 1965).

At sites with two-dimensional heterogeneities (linear tectonic infringement or anisotropy of one preferred orientation), a more complex behavior in the ρ_a and dH plot dependence was observed. Thus, a direct correlation for B-polarized and inverse correlation for the E-polarized field were observed.

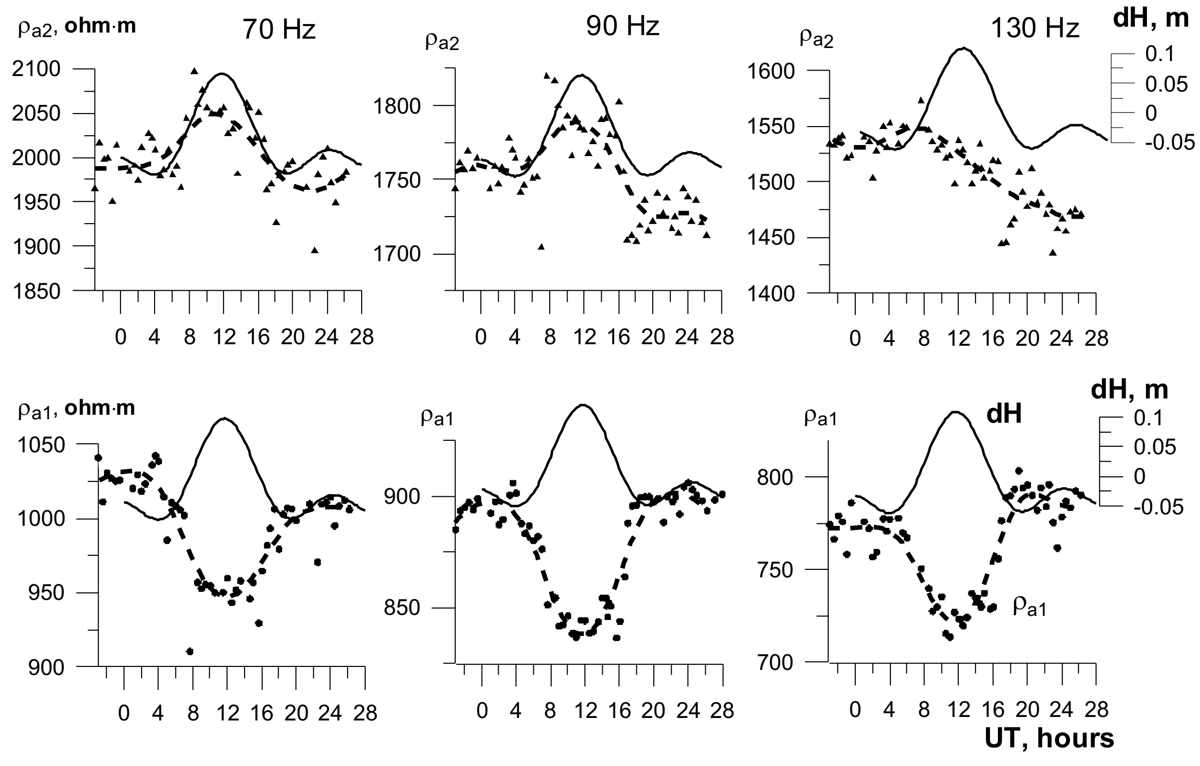

FIGURE 8 | **Monitoring results at the site on the Karelia isthmus (26.07.1998). Dotted lines are smoothed apparent resistivity plots.**

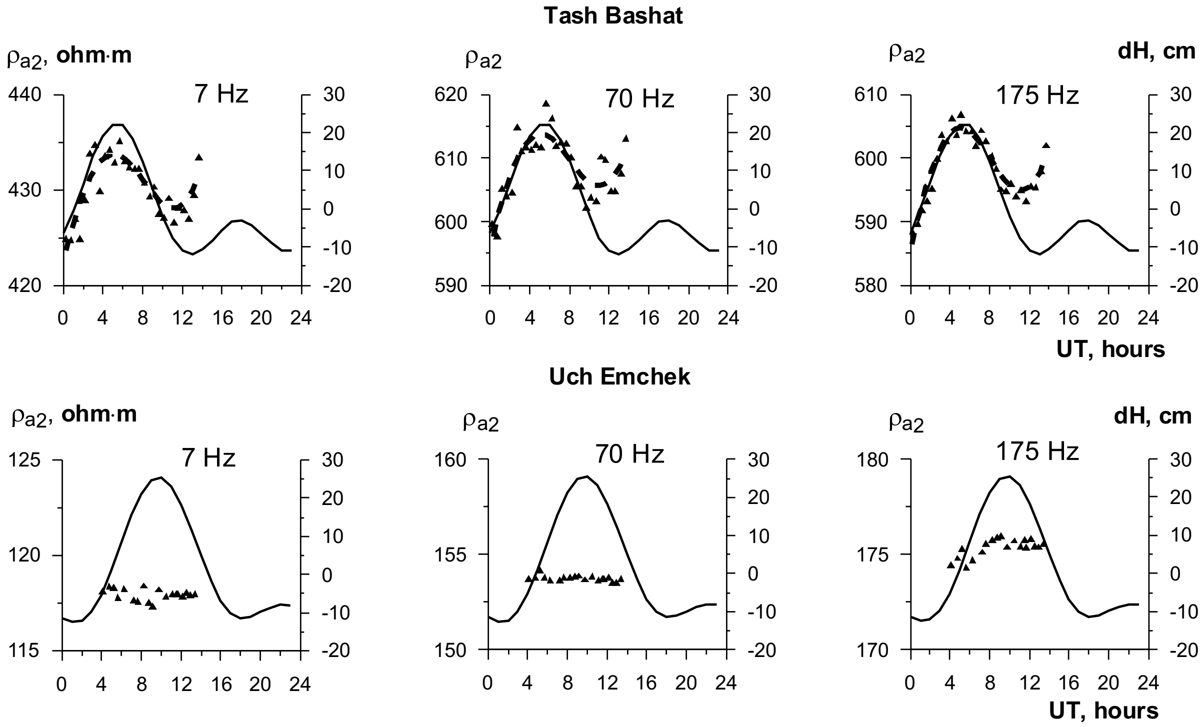

FIGURE 9 | **Monitoring results at the Tash Bashat (4.06.2005) and Uch Emchek (27.05.2005) sites in the Bishkek region. Dotted lines are smoothed apparent resistivity plots.**

The experiments described show the variations of the apparent resistivity associated with tidal effects during the monitoring using the audiomagnetotellurics (AMT) method. The conditions at which these tidal variations of apparent resistivity can be observed were identified. At the same time, the mechanisms for these variations in non-uniform and anisotropic media are not completely clarified, requiring further experimental studies.

CONCLUSIONS

1. Natural electromagnetic field measurements in the audio frequency range allow us to find a good correlation between apparent resistivity variations and tidal deformations of the Earth's crust. ρ_a variations of 3-8 % are connected with vertical tidal deformations, dH, of 0.15 - 0.3 m.

2. Apparent resistivity tidal variations are observed in heterogeneous geological environments. At the sites with thick homogeneous sedimentary cover, significant ρ_a changes are not observed.

3. Both direct and inverse correlations between ρ_a and dH plots were observed. These correlations can be explained depending on the degree of rock water saturation. The ρ_a and dH inverse correlation appears in the water-saturated rocks with low resistivity and the direct correlation appears in dry rocks with high resistivity.

4. Monitoring at the site with anisotropic rocks presents a different correlation behavior for E- and B-polarized fields. In the analyzed experiment, an inverse correlation was obtained for E-polarization and a direct correlation was obtained for B-polarization.

5. The high accuracy of apparent resistivity measurements (not more than 1 % error) using modern AMT instruments allows us to study its small changes (2-3 %). The AMT sounding method can be applied to the monitoring of the rock stress-strain state prior to an earthquake.

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