Processing, analysis and interpretation of time-frequency series for magnetotelluric monitoring

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Abstract. This work presents the results of processing and interpretation of data of magnetotelluric monitoring obtained in the territory of the Bishkek geodynamic station (Northern Tien Shan). A new approach to the analysis of magnetotelluric monitoring data is proposed. The correlation of the obtained time-frequency series of variations of electromagnetic parameters with the moon-solar tidal effects, deformations of the Earth's crust, variations of apparent resistance and the distribution of seismicity was performed. A concept, linking the change in the stress-strain state of the medium with the redistribution of fluids between fracture systems, which causes variations in electrical resistance, was confirmed.

1. Introduction
Geodynamic processes, which are monitored on the territory of the Bishkek Geodynamic Proving Ground (BGPG), have a significant impact on the electrical properties of the geological environment [1-4]. Under the conditions of submeridional compression of the intracontinental Tien Shan orogene, both changes in the electrical properties of the geological environment (the first kind effect) and changes in the intensity of the electromagnetic fields generated there (the second kind effect) are possible [5]. These phenomena make it possible to study geodynamic processes occurring in the crust and upper mantle using electromagnetic methods. Performing the monitoring studies to predict catastrophic events of natural or man-made origin by the method of magnetotelluric sounding may be the most effective one. At the same time, interest in studying of lunar-solar influences and their correlation with changes in geophysical fields is currently growing, which is due to the possible use of such correlations in studying the geological processes occurring in the Earth's crust. This becomes especially relevant when implementing complex geophysical monitoring conducted on the territory of the BGPG, the main purpose of which is to study the patterns of seismic processes under conditions of submeridional compression of the Earth's crust [3, 4].

2. Data and methods
During geophysical monitoring, along with seismological data obtained from a network of seismic stations, data of electromagnetic, geodesic, gravimetric and other types of observations are collected (accumulated) on the territory of BGPG [1, 4]. All the results of complex geophysical monitoring are stored in a database on the server of the Research Station of the Russian Academy of Sciences, with the aim of further using these data for complex interpretation of geophysical data. Electromagnetic monitoring is carried out in two versions with controlled and natural sources that have different depths of research - sounding the formation of a field in the far zone (the source is an EGS-600-2 electro impulse system) and magnetotelluric (MT) monitoring, where the natural electromagnetic field is used as a
source. The method of processing and interpreting the MT monitoring data includes plotting the frequency dependences of the components of the impedance tensor and their transformants - curves of apparent resistance and impedance phases and building time-frequency series of electromagnetic parameters for monitoring observation points. The processing of MT-monitoring data has some peculiarities as compared with the conventional processing technique: phase curves were chosen as reference curves, since they are considered to be more stable [6]; the use of histograms has significantly improved the quality of phase curves, and, consequently, simplified editing; the use of the dispersion ratio of the phase curves and the curves of apparent resistances also contributed to the improvement of the quality of the resulting. In this work, we continue research related to the development of the azimuthal MT-monitoring technique, which consists in analyzing the obtained time series of electromagnetic parameters in order to determine the contribution of each of the components of the impedance tensor to the information content of monitoring studies [3, 4]. The azimuthal MT-monitoring technique [3] for assessing the study of the characteristics of variations in electrical resistance includes the following procedures: 1) calculating variations of apparent resistance and impedance phase for 12 azimuths, in the interval from 0.01 to 10 sec (the duration of time series at point observations must be at least 24 hours); 2) the calculation of the correlation of variations of the resistance and phase of the impedance with the components of the lunar-solar tides depending on the period of soundings and azimuth; 3) comparison of tidal effects with pseudo-cuts of variations in electrical resistance in order to analyze the response of electrical conductivity variations to the elastic deformations of the Earth's crust from lunar-solar tidal influences. The most compact form of representation of the time-frequency structure of the components of the electromagnetic field transfer operators is their pseudo-sections — maps with the observation time horizontally and the depth parameter (the logarithm of the period) vertically. The time series of "azimuthal" MT-monitoring consists of several time-frequency diagrams (pseudo-sections) according to the number of azimuths for which the impedance tensor is recalculated (Figure 1). The logarithm of the probing period (T) characterizing its depth is plotted along the vertical axis of the pseudo-sections. The pitch along the horizontal axis of the pseudo-sections (time axis t) is a unit time interval within which MT sounding is processed to calculate apparent resistivity values in the working interval of periods T.

![Figure 1. Scheme of points of geophysical observations on the Kentor mini-poligon. MT-soundings are shown by circles (1), monitoring observation points are marked with stars (2), line-angular observation points are marked with triangles (3), and active faults (4)](image-url)
On the time-frequency diagrams for the current time interval (t) and for the period of sounding, variations of electromagnetic parameters are deposited, i.e. the difference between the average and current values, for example, the apparent resistance at the considered azimuth.

3. Results and discussion

We assume that during the compression of the Earth's crust due to the interconnectivity of fluid-filled microcracks in rocks, there is a redistribution of fluids between fracture systems, which leads to a decrease in the resistivity of rocks in the direction of compression [1, 3, 7]. When expanding, respectively, the opposite process should occur, so, the resistivity of the rocks increases in the direction of expansion. This hypothesis is confirmed by the results of experiments, including those in the territory of the Central Tien Shan [3, 4, 7]. The change in electrical conductivity and other electromagnetic parameters of the Earth's crust is not a factor itself that could directly affect the geological environment. However, this change can cause the occurrence of natural and artificial electromagnetic fields, both in the upper part of the Earth's crust and in the surface layer of the atmosphere. In addition to changes in electrical conductivity during deformations of the rocks of the earth's crust, other effects arise that can cause changes in the electric and magnetic fields, such as piezoelectric, piezomagnetic and tectomagnetic, but these effects are very difficult to isolate in the general electromagnetic background.

For all items of MT monitoring (mode, profile, stationary) in the territory of BGPG, the estimates of correlation coefficients of variations of the module of apparent resistance and impedance phases with lunar-solar tidal influences, determined using the Tide.exe program, are shown in diagrams. Analysis of the correlation relationships between variations of apparent resistance and lunar-solar tides indicates the existence of a relationship between these phenomena (Figure 2).

![Figure 2](image)

**Figure 2.** Correlation polar diagrams for the Kentor mini-polygon: a) - location of monitoring points and faults: 1 - Shamsinsky regional fault, 2 - local faults, 3 - MT-monitoring point, 4 - points of remote-ranging observations. Correlation diagrams for variations of apparent resistance (dRo) at FT-0 and: b) by the northern component of lunar-solar tidal effects (Av), c) by changes in the lengths of the base lines between points K5 and K2 according to the results of distance ranging observations.

To compare the time-frequency series of electromagnetic parameters with gravitational tidal effects in different geological and tectonic conditions, we propose a way to present the results in the form of correlation polar diagrams. Based on the analysis of the behavior of the electromagnetic and gravitational fields in comparison with the geological and tectonic structure of the monitoring points, their strain sensitivity was assessed. The results of MT-monitoring allow us to conclude that under the influence of lunar-solar tides, the maximum variations in apparent resistivity occur in stress-sensitive zones confined to fault structures. The high level of the values of the correlation coefficients, as a rule, indicates the strain sensitivity of the zone of dynamic influence of the fault in correlation with the lunar-solar tides. In order to study the connection of deformation processes with the characteristics of
variations of geophysical fields at the Kentor mini-poligon (Figure 1), the Research Station of the Russian Academy of Sciences in 2014 conducted observations on the Kentor line-angular measurement network and electromagnetic sounding using the azimuthal magnetotelluric monitoring method. The network of remote-range observations consists of six points, with the main focus on the study of deformation processes in the Shamsi-Tyundyuk fault zone. The network of MT-monitoring points in the territory of the Kentor mini-poligon, consisting of three points (Figure 1), was laid in various geoelectric conditions. Point “0” on the Kentor West profile is located on the northern slope of the Kyrgyz Range on the Paleozoic rocks overlapped with a cone, point “4” on the Kentor Central profile is located directly above the Shamsi-Tyundyuk fault zone, and point “16” on the Kentor West profile is located on Neogene-Quaternary sediments of the Chui basin. Figure 3 shows the time-frequency series of azimuthal MT-monitoring of apparent resistance from point “0” on the Kentor West profile in comparison with seismicity. In the time interval of 6–9 hours, for periods of 1–100 sec, a decrease in apparent resistance is observed at azimuths of 30°–60°, and an increase in azimuths of 120°–150°. The difference in azimuths of oppositely directed variations is about 90°, i.e. variations of apparent resistivity during this time interval may be due to the redistribution of fluid in the pore-fractured space and are "coherent in azimuths of 45° and 135°". Furthermore, along the time series in the time interval of 9-12 hours, variations coherent in azimuths of 60° and 150° are observed. In the range of 25–30 hours, a very contrasting radial variation in the range of periods 0 <logT <2 is distinguished. Figure 2 presents the results of the experiment of simultaneous registration on the Kentor line-angular measurement network and MT-monitoring. In general, the characteristic of correlation dependences suggests that sources of deformation processes, apart from periodic tidal influences, are also sources of a different nature. There is a significant similarity for point 4, which is installed directly above the Shamsi-Tyundyuk fault zone (Figure 1) in the correlation diagrams of variations of apparent resistance between the components of lunar-solar tides and changes in baseline lengths. Situation is similar for points located in other geological and tectonic conditions. Although the difference in the morphology of the correlation fields for different observation points is significant, it is probably due to the presence and orientation of large geoelectric structures that characterize the electric conductivities caused by the distribution of pore fracture fluids. Variations of apparent resistivity are formed with changes in the lengths of baselines and with tidal effects on two-dimensional correlation diagrams of correlation fields of similar shape and orientation. This indicates a relationship between tidal effects, deformation processes, and variations in electrical conductivity. The level of correlation coefficients of 0.4–0.5 in the diagrams is obviously related to the low energy of tidal impacts and the insufficient accuracy of determining estimates of variations in apparent resistance and baseline lengths, but the selection of stable-form correlation fields indicates the relationship between the processes under consideration. Theoretical calculations of gravitational tidal effects are confirmed by experimental observations for the territory of the Bishkek geodynamic station in [3]. To verify the calculated data, the Research Station of the Russian Academy of Sciences performs observations using the Scintrex CG-5 Autograf gravimeter, which is installed in a gallery with a constant temperature of + 8° in the territory of the Research Station (30 km from the city). Observations are carried out at intervals of 12 s, and then during processing they are averaged at intervals that are necessary for the tasks and the required data discretization. It should be noted very high quality of the observed data (about 0.001 mGal). Interferences in this case are seismic events that are clearly recorded by a gravimeter, which is a Golitsyn pendulum. Thus, the completed studies complemented the existing database, including both magnetotelluric fields and their transformations, determined during measurements using the Phoenix MTU-5 broadband equipment, and the corresponding seismic activity parameters (KNET network) of the region under study (magnitude of seismic event magnitude, distance from the epicenter of the earthquake, clusters of seismic events). The work carried out showed the need for the use of MT-monitoring of the environment with the placement of observation points in seismically active fracture zones filled with decomposed rocks with increased water content and low resistivity at the so-called stress-sensitive points. It seems that such structures, including conducting core objects, can be combined into a single BGPG seismic monitoring system. In this case, MT-monitoring can be an effective tool for studying geodynamic processes, as well as physical mechanisms controlling the change
in the geoelectric state of the environment. In the time-frequency series of apparent resistance at moderated monitoring points of the Kentor mini-poligon, anomalies of electromagnetic parameters have been identified, corresponding to the fluid redistribution model in the porous-fracture space, that is, in-phase reduction and increase in the parameter values on orthogonal azimuths (Figure 3). Thus, a phenomenological model has been tested that relates the change in the stress-strain state of the medium to the redistribution of fluids between fracture systems, which causes variations in the active and reactive components of electrical resistance.

![Image](image.png)

**Figure 3.** Time-frequency series of azimuthal MT-monitoring of apparent resistance from point “0” on the Kentor West profile in comparison with seismicity. Moments of earthquakes are shown by arrows

4. **Conclusion**

An interdisciplinary approach to solving the problems of complex geophysical monitoring of the territory of the Bishkek Geodynamic Proving Ground makes it possible to create new methods for studying the ongoing geodynamic processes (determining and preventing dangerous geological processes), including seismic events. The research resulted in the following:

- the depths of the geoelectric profile, which are most sensitive to the influence of geodynamic processes, have been determined;
- in the recorded time series of electromagnetic parameters, it was possible to isolate the characteristic signs of changes in the stress-strain state of the environment due to seismic events;
  - it has been shown that a significant part of earthquake hypocenters is confined to gradient zones near the contacts between blocks or bodies with contrasting geoelectric parameters;
  - an assessment of the informativeness of additional impedances was made, on the basis of which it was concluded that the use of this parameter is promising for evaluating the strain sensitivity of observation points;
- as a result of the correlation analysis of gravitational tidal effects with magnetotelluric parameters, it was found that the nature of the relationship depends on the geoelectric structure of the sensing point and is reflected in the distribution of stable clusters in the correlation polar diagrams;
- the concept linking the change in the stress-strain state of the medium with the redistribution of fluids between fracture systems, which causes variations in the active and reactive components of electrical resistance, was confirmed.

5. **Acknowledgments**

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