Analysis of synchronous magnetotelluric and magnetovariational regime observations for the Kentor mini test polygon

V E Matiukov, E A Bataleva
Research station of Russian Academy of Sciences in Bishkek city, 720049, Bishkek-49, Kyrgyzstan
E-mail: vitaliy@gdirc.ru

Abstract. The paper discusses various approaches for processing and analysis of synchronous magnetotelluric and magnetovariational data obtained at the Kentor mini test polygon, which is located in the Baytic basin of the Chui region of Kyrgyzstan. The versions of noise reduction of received electromagnetic signals at the stage of robust processing are considered. The materials were processed using a remote reference technique for possible noise detection and calculate the additional components, such as a horizontal magnetic tensor for further interpretation of the obtained data. The dynamics of changes in the geoelectric cross-section for 2 sessions of researches by the tested profiles is considered.

1. Introduction
One of the main stages of the qualitative application of the magnetotelluric (MT) sounding method, both in monitoring and profile observations, is the processing of field material is used, which makes it possible to stably determine the components of the impedance tensor and their transformants on the Earth's surface from time records of the natural electromagnetic field. Recently, significant success in improving the quality of processing has been achieved by using robust statistics. The first works on the processing of MT data using the robust statistics appeared in the late 80s - early 90s, pioneering can be considered the works of Chave A.D. and Thomson D.J., for example [1], which used the robust M-Hubert estimate of the regression problem, replacing the technique of least squares. The application of this approach made it possible to reduce the effect of noise on the results of calculations of the impedance tensor components. However, the development of effective processing procedures remains a very difficult and actual problem, as the researches are realized in a very wide frequency range (10^3-10^4 Hz), and it is also necessary to allow for the effect of mass factors that can decently affect the processing results. The paper presents the results of estimate of efficiency by using the remote reference technique for noise reduction of different nature on synchronous recordings of a MT field. To date, various methods of processing MT data have been developed. From these methods, we can note the often used narrow-band filtering method developed in the works of V.N. Astapenko M.N. Berdichevsky, I.A. Bezruk, O.M. Chinareva. The most used approach to the processing of magnetotelluric data is based on the use of spectral analysis of correlation functions. This method is the basis of processing programs (fast Fourier transform, created in Russia by V.Yu. Semenov and Iv.M. Varentsov [2]). All methods of spectral analysis in combination with the technique of least squares give the almost same results in the case when the raw data is not noisy. However, if the MT data contains various types of noises, the
situation changes significantly, especially with regard to the technique of least squares, which is used to solve a redundant system of equations for MT transfer functions and is very sensitive to the presence of noise. The modern practice of MT studies on the territory of the Bishkek Geodynamic Proving Ground and adjacent territories is based on a joint analysis of electromagnetic fields recorded synchronously at ordinary sounding points on the profiles or in a strain-sensitive point and in a common remote observation point, which are stationary or any ordinary sounding point, where the noises are almost miss, and observations are realized synchronously. Such a field observation scheme to allow the noise reduction when estimating of traditional local transfer operators, such as impedance tensors [Z] and Wiese-Parkinson's matrices [W], and at the same time obtain new electromagnetic parameters for interpretation, for example, a horizontal magnetic tensor [M] - connecting horizontal fields at two points.

Since 2003 to the present, the Research station of the Russian Academy of Sciences (RS RAS) has been realized the MT and magnetovariational studies using Phoenix-MTU-5 equipment. In the Tien Shan and adjacent territories, researches are performed in various directions, including using other geophysical methods, modern techniques and equipment [3-9]. Explore the results of processing, using the remote reference method, of profile monitoring materials realized in the Baytic basin of the Northern Tien Shan in 2014 and 2015. Observations at ordinary points were execute in pairwise-synchronous regime (Figure 1) and were accompanied by simultaneous recordings of Phoenix-MTU-5 stations located at base points (Chon-Kurchak and Ak-Suu stationary points).

In the conditions of the mountainous terrain of the Tien Shan, the practical application of the MT method is complicated by the difficulties in choosing suitable sites for installing the measuring system, which does not allow ensuring a uniform location of sounding points along the survey profile. Considering this circumstance, the Kentor mini test polygon was insert in such geological conditions (Figure 1), so that, on the one hand, it was possible to monitoring the modern active fault structure by various geophysical methods, on the other hand, the level of industrial noises remained within acceptable
limits. Unfortunately, some of the records of the electromagnetic field were complicated by industrial and household noises, which, as a rule, leads to the appearance of large errors in the determination of electromagnetic parameters. Therefore, in addition to the generally accepted methodological techniques (performing control points, i.e., realizing the verification works to determine the reliability of field measurements during each monitoring session), the remote reference technique was used to suppress the influence of uncorrelated noises in electrical channels.

2. About the measurement accuracy of the Phoenix MTU-5 equipment

The purpose of the MT data processing is to obtain from the recorded noise-like signals information about the conductivity structure of the underlying medium in the form of a set of smooth functions reflecting the electrical properties of the earth's crust and upper mantle. The main of these functions are impedance and tipper relationships by the frequency from which transformants are calculated, for example, apparent resistivity curves over various azimuths. Noise level estimates are also provided, such as coherence between field components, parameters dispersions and signal-to-noise ratio, on the basis of which confidence intervals of parameters are calculated. The accuracy characteristics of the electromagnetic parameters obtained by the MTU-5 stations are primarily determined by the time stability of the hardware response [10].

Currently, the workers of the RS RAS on the territory of Tien Shan, on the basis of the generally accepted method of researches [10], in the process of performing MT soundings, the following characteristics of the measuring system are monitored at least once every 3 months: the stability of the channel transmission coefficient and the shape of the amplitude-phase frequency characteristic. At different times, calibrations and various tests of all measuring channels and sensors showed the high stability of the Phoenix MTU-5D measuring system, so the changes in the parameters of the hardware characteristics during these checks did not exceed 0.2%.

It is known that in the presence of noises in the measurements, the estimates of MT parameters can be significantly shifted [11].

The problem of obtaining the impedance tensor is reduced to finding the coefficients in linear relationships between the components of the electromagnetic field in the frequency domain. The system of equations for finding the elements of the impedance tensor:

\[ E_x(f) = Z_{xx}(f)H_x(f) + Z_{xy}(f)H_y(f) \]
\[ E_y(f) = Z_{yx}(f)H_x(f) + Z_{yy}(f)H_y(f) \]

are two complex equations with four complex unknowns. The solution can be executed by (a) averaging measurements made at different time intervals, since \( Z_{ij} \) does not change in time, (b) averaging a certain number of measurements at close frequencies, as the impedance changes with a frequency quite smoothly. Multiplying both parts of the equation by complex conjugate components of the strength of the electric or magnetic field, we obtain a redefined system for finding estimates of \( Z \). The solution of such system for \( Z_{xy} \) at frequency \( f \) is written in the next form:

\[ Z_{xy} = \frac{(E_xH_y)(H_xH_y) - (E_xH_x)(H_yH_y)}{(H_xH_x)(H_yH_y) - (H_xH_y)(H_yH_x)} \]

where \( H_x, H_y \) - complex-conjugate values. In this case, the products \( (H_xH_x) \) and \( (E_xH_x) \) are estimates of auto and relative (cross) spectra of power densities of the electromagnetic field signals. The presence of noise, for example in magnetic field signals, can shift the auto spectrum \( (H_xH_x) \), thereby shifting up or down the estimates of the \( Z \) impedance tensor elements.

A technique that reduces displacement errors by using cross-correlation between two synchronous recording points is called the remote reference observation technique [12]. Its essence is to perform synchronous measurements by two additional independent channels \( R_x \) and \( R_y \). As base channels, measurements from magnetic sensors located at a distance of several hundred meters to 100-200 km from the sounding point, depending on the main sources of noises, are usually chosen.
The impedance estimates in terms of spectral power densities using the magnetic channels of the remote base point is called the impedance RR estimate. The expression for the impedance RR estimate \[13\] is:

\[
Z_{xy} = \frac{(E_x R_y)(H_x R_x) - (E_x R_x)(H_y R_y)}{(H_x R_y) - (H_x R_y)(H_y R_y)}
\]

If the noises are not correlated with useful signals, then the impedance RR estimates obtained from the base channel equations will be unbiased, as the last expression includes only relative spectral power densities.

The impedance tensor bias is quantified by the coherence coefficient. We introduce the concept of coherence. Coherence can be considered as a quantitative measure of the tightness (quality) of linear communication for two data series (signals) \[2\]. Coherence determines the consistency of the change in phase difference between the two-time data series. For two data series \(A(t)\) and \(B(t)\), the coherence function \(\text{Coh}_{AB}\) is the relationship of the relative spectral density of the sequences \(A(t)\) and \(B(t)\) to the product of the auto-spectra of the data series \(A(t)\) and \(B(t)\):

\[
\text{Coh}_{AB} = \frac{(AB)}{(AA)^{1/2}(BB)^{1/2}}
\]

Then in terms of coherence, this equation can be represented as

\[
Z_{xy} = \frac{|E_x|}{|H_y|} \left( \frac{\text{Coh}_{E_x R_y} \text{Coh}_{H_x R_x} - \text{Coh}_{E_x R_x} \text{Coh}_{H_y R_y}}{\text{Coh}_{H_x R_y} \text{Coh}_{H_y R_y} - \text{Coh}_{H_x R_y} \text{Coh}_{H_y R_x}} \right)
\]

For the single (local) sounding \(\text{Coh}_{H_x R_y} = \text{Coh}_{H_y R_y} = 1\) and \(\text{Coh}_{H_x R_x} = \text{Coh}_{H_y R_x}\). Thus, the equation for \(Z_{xy}\) is reduced to the following in the case of using local magnetic field components:

\[
Z_{xy} = \frac{|E_x|}{|H_y|} \frac{\text{Coh}_{E_x H_y} \text{Coh}_{H_x H_y}}{1 - |\text{Coh}_{H_x H_y}|^2}
\]

From the analysis of the last expression, it follows that for small values of \(\text{Coh}_{H_x H_y}\), the impedance is proportional to \(\text{Coh}_{E_x H_y}\). Obviously that coherent noise in the \(E_x\) and \(H_y\) channels will worsen the process of the impedance estimating.

The last equation for small quantities \(\text{Coh}_{H_x R_y}\) is reduced to the next form:

\[
Z_{xy} = \frac{E_x \left( \text{Coh}_{E_x R_y} \right)}{H_y \left( \text{Coh}_{H_y R_y} \right)}
\]

Accordingly, the impedance estimate is directly proportional to the coherence. Coherence is a measure of the "similarity" (consistency or correlation) of two processes and reflects the degree of noise influence - the higher the coherence, the smaller the contribution of noises and the more similar the signal changes over time on both channels and vice versa, the more noises, the coherence is closer to 0.

A coherent criterion of partial impedance estimates for diagnosing the quality (distortions) of estimates of magnetotelluric transfer functions obtained during the registration of the electromagnetic field for the Central and Eastern profiles of Kentor mini test polygon is applicable. Figure 2 shows a pseudo-section of Ex-Hy coherence values corresponding to the \(Z_{xy}\) impedance estimates.
Figure 2 - Ex-Hy Coherence pseudo-section for Central and Eastern profiles of Kentor mini test polygon.

From this figure, we can conclude that there is no significant decrease in the values of the multiple coherence coefficient in almost the entire range of periods, i.e., the quality of the studied linear connections does not decrease, which indicates about reliability of the obtained impedance estimates and the possibility of their effective use both in structural studies and for analyzing the dynamics of the parameters of the geoelectric cross-section.

3. Remote reference data processing technique

Magnetotelluric data obtained from stationary points and as a result of profile and regime observations contain not only useful signals, but also the noises of both artificial and natural origin. Various types of noises are one of the main problems of magnetotelluric method (noises is usually understood as fields of relatively close sources that cannot be approximated by a plane wave). Depending on the noise’s types, the radius of their action also changes. The most complete overview of the main noise’s types is presented in [13]. It follows that further processing of the obtained data requires a thorough analysis of the obtained material - magnetotelluric time series and estimations of transfer functions based on them.

When using the remote base technique, it is important to understand what distances use for effectively position of the base point. For general reasons, clearly that the remote base should not be too close to the measurement points to fall within the noise range and not too far for the MT fields at the profile and base points keep as linearly connected. It is natural to assume that the optimum position of the remote base will depend on the nature of the noise and the useful signal. Many articles are devoted to this issue, for example [14]. However, in most cases, studies are limited to individual examples.

Observations at ordinary points were execute in pairwise-synchronous regime and were accompanied by simultaneous recordings of Phoenix-MTU-5 stations located at base points Chon-Kurchak and Ak-Suu (Figure 1).

As an example of using the remote reference technique, we will give the results of processing of 6-9 points on the Kentor Central profile for 2014 and 2015 (Figure 3).
Based on the results of comparison, it is possible to notice insignificant differences in the results of processing MT data with a single-point and remote reference technique, which are not significant, but only complement each other, in the case when the observed curves of apparent resistivity and impedance phases of good quality - 8, 9 sounding points for 2014 (Figure 3). If the quality of the apparent resistivity curves and impedance phases is moderate, then remote reference processing can even degrade the quality of the obtained material, for example, 6, 7 sounding points for 2014 (Figure 3).

4. Plotting the geoelectric models along Kentor East profile

A Two-dimensional smoothing inversion of MT data for plotting geoelectric models along the Kentor East profile for May 2014 and 2015 was realized using the Rodi-Mackie program [15]. The program implements the nonlinear conjugate gradient method, which attempts to minimize the objective function, which is the sum of the normalized data residuals and model smoothness. The trade-off between data residuals and model smoothness is controlled by the regularization parameter $\tau$. Parameter $\tau$ is set manually by the user.

The longitudinal and transverse curves of apparent resistivity, impedance phases, and tipper were selected as input data for inversion along the Kentor East profile at 26 observation points in the interval of periods from 0.01 to 1600 s. The grid of the approximation model consists of 162 cells horizontally, sparse at the edges of the model and more frequent in the vicinity of points, 107 cells vertically, increasing in size with depth. By drawing a grid, the terrain is taken into account. Starting model resistivity – 100 Ohm*m. The error limits of inverted data are as follows: apparent resistivity modulus (TE mode) - 100%, apparent resistivity modulus (TM mode) - 30%, impedance phase (TE mode) - 5%, impedance phase (TM mode) - 5%, tipper - 0.05%. As a result of several test calculations of the inversion for each year of research, the value of the regularization parameter $\tau$ was chosen equal to 3. As a result of performing 200 iterations, models were obtained for each year of research, which are shown in Figure 4. The value of the RMS residual was 1.14 for the data of 2014 and 1.17 for 2015 data.
According to the calculated geoelectric models, it is possible to see the correspondence (with small changes in geometric shape) of conducting zones 1-4, including the Shamsy fault zone (Figure 4), as well as zones with high resistivity 5-7, which can be considered a fairly good result of regime monitoring.

5. Conclusions
The pseudo-sections of the coherence values indicate the sufficient reliability of the obtained impedance estimates and the possibility of their effective use both in structural studies and for analyzing the dynamics of the parameters of the geoelectric cross-section. The remote base processing technique in the experiment realized at the Kentor mini test polygon in 2014-2015 did not introduce radical changes in the distribution of variations in apparent resistivity and impedance phases, which may be due to the fact that the level of noise at the point of sounding is significantly lower than at the base point. However, the results obtained using this technique are used to obtain such an important additional parameter for magnetotelluric studies as the horizontal magnetic tensor connecting the horizontal magnetic components at different points, which can be determined with good accuracy for distances between points up to 500 km. The geoelectric cross-sections obtained from the results of the inversion of magnetotelluric and magnetovariational data are quite well combined with each other, which is correspond with the results of modern studies.

6. References
[1] Chave A, Thomson D, Ander M 1987 On the robust estimation of power spectra, coherences, and transfer functions. *J Geophys Res* **92** pp 633–648. https://doi.org/10.1029/JB092iB01p00633
[2] Varentsov Iv M 2016 Development of PRC_MTMV software for multisite processing of simultaneous MT/MV sounding data *Voprosy Yestestvoznaniya* **3** pp 48-52 (in Russian). http://dx.doi.org/10.13140/RG.2.1.2269.1449
[3] Bataleva E A, Mukhamadeeva V A 2018 Complex electromagnetic monitoring of geodynamic processes in the Northern Tien Shan (Bishkek geodynamic test area) Geodynamics & Tectonophysics 9 2 pp 461–487 (in Russian). https://doi.org/10.5800/GT-2018-9-2-0356

[4] Rybin A K, Bataleva E A, Matiukov V E 2018 Detalization of geoelectric structure of the joint zone of the Chui basin and Kyrgyz ridge (Minipoligon Kentor) Vestnik KRSU 18 10 pp 134-140 (in Russian) https://www.elibrary.ru/item.asp?id=36979491

[5] Bataleva E A, Batalev V Yu 2018 Anisotropy of electrical conductivity of seismically active regions (based on the results of magnetotelluric monitoring) Materials of VI International Symposium «Problems of geodynamics and geology of intracontinental orogens (19-24 June 2017, Bishkek). Bishkek RS RAS pp 346-352 (in Russian) https://www.elibrary.ru/item.asp?id=36671701

[6] Bataleva E A, Rybin A K, Matiukov V E 2019 System for collecting, processing, visualization and storage of the MT-monitoring data Data 4 99 https://www.mdpi.com/2306-5729/4/3/99. https://doi.org/10.3390/data4030099.

[7] Batalev V Yu, Bataleva E A, Matiukov V E, Rybin A K Study of irreversible deformations in the Tien Shan lithosphere based on magnetotelluric data (methodological aspect) Vestnik KRAUNTS 2019 42 2 pp 42-56. doi: https://doi.org/10.31431/1816-5524-2019-2-42-42-56 (in Russian)

[8] Bataleva E A, Matiukov V E 2019 Deep structure of the Baytic basin (Northern Tien Shan) Deep structure, geodynamics, thermal field of the Earth, interpretation of geophysical fields. The tenth scientific readings in memory of Yu.P. Bulashevich. Conference materials Yekaterinburg IGF UB RAS pp 24-28 (in Russian) http://igfuroran.ru/images/conference/Bulashevich/2019_Bulashevich_materialy.pdf

[9] Rybin A, Bataleva E, Nepeina K, Matiukov V, Alexandrov P, Kaznacheev P 2020 Response of cracking processes in variations of geophysical fields Journal of Applied Geophysics V 181 https://doi.org/10.1016/j.jappgeo.2020.104144

[10] Fox L 2001 Satellite-Synchronized 3-D Magnetotelluric System U.S. Patent № 6 191 587 B1.

[11] Goubau W M, Gamble T D, Clarke J 1978 MT data: removal of bias Geophysics 43 pp 1157-1162. http://dx.doi.org/10.1190/1.1440885

[12] Semenov V Yu 1985 Data processing of MT soundings (Moscow: Nedra) p 133

[13] Vozoff K 1991 The Magnetotelluric Method Electromagnetic Methods in Applied Geophysics Volume 2 Application, Parts A and B Tulsa: SEG pp 641–711 https://doi.org/10.1190/1.9781560802686.ch8

[14] Gamble T D, Goubau W M, Clarke J 1979 Magnetotellurics with a remote magnetic reference Geophysics 44 pp 53-68 https://doi.org/10.1190/1.1440923

[15] Rodi W L 2001 Nonlinear conjugate gradients algorithm for 2-D magnetotelluric inversion Geophysics 66 pp 174-187. http://dx.doi.org/10.1190/1.1444893

Acknowledgments
The results presented in this work are received within performance of the state assignment of Federal state budgetary institution of science of the Research station of the Russian Academy of Sciences in Bishkek for 2019-2021 on subject AAAA-A19-11902019063-2.