Magnetotelluric monitoring of geodynamic processes

Boris S. Svetov ([1]), **Sergej D. Karinskij** ([1]), **Yurij I. Kuksa** ([1]) **and Vladimir I. Odintsov** ([2])
([1]) *Institute of Physics of the Earth, Russian Academy of Sciences, Troitsk, Moscow Region, Russia*
([2]) *Institute of Terrestrial Magnetism, Jonosphere and Radio Wave Propagation, Russian Academy of Sciences, Troitsk, Moscow Region, Russia*

Abstract
Electromagnetic (EM) monitoring of geodynamic processes can be based on the two different seismo-electrical phenomena: a change in resistivity of some geological cross-sections and a generation of EM fields of internal (geodynamic) origin. Continuous observation of the natural magnetotelluric (MT) field simultaneously provides information on both such phenomena. The transfer functions between components of the MT field reflect geoelectrical section and the residual field includes the EM field of internal origin. Their variations in time give independent information on geodynamic processes. The transfer functions and the residual field can be determined by known deterministic methods, although it appears more convenient to apply the methods of adaptive data processing. They elicit information on both phenomena in real time. Continuous MT observations were carried out at the Bishkek geodynamic testing ground (Kirgizia) during 1993. Their results show how informative MT monitoring is.

Key words *electromagnetic monitoring – seismo-electrical phenomena – magnetotelluric field – transfer functions – adaptive data processing*

1. Geophysical motivation

It is known that two different types of seismo-electrical phenomena occur, that can be regarded as two main effects for EM monitoring of geodynamic processes. The first one is a change in the electrical properties of rocks and a corresponding change in geoelectrical cross-section. Earthquake preparation is accompanied by rock cracking, pore space deformation and by forced redistribution of water solution. Such processes cause a change in the resistivity and chargeability of rocks. The relative variation of a resistivity in porous rocks can be greater than the relative effect associated with rock strain even by some orders of magnitude (a resistivity coefficient of relative tensosensitivity may be $10^4 \div 10^6$) (Sobolev, 1995).

A second type of such phenomena is the direct generation of EM fields as a result of mechanic-electric energy transformation. A specific mechanism for such transformations depends on the structure and composition of rocks and on the type of rock deformation and consequently on the timephase during earthquake preparation. Evidently, electrokinetic processes play a principal role under elastic deformations of water saturated rocks. In a first approximation the mechanic-electric transformation is linear in the case and the frequency spectrum of EM disturbances is a linear function of the mechanical field variations. In such a case the frequency band starts from some almost constant fields, and reaches a few hundred hertz. In contrast, under plastic deformations and

Mailing address: Dr. Boris S. Svetov, Institute of Physics of the Earth, Russian Academy of Sciences, Troitsk, Moscow Region, 142092 Russia; e-mail: svetov @igemi.igemi.rssi.ru

failures mechanic-electric transformations may not be linear and the EM spectrum may run into kilo and megacycles (Sobolev, 1995).

At present, we have gained some important experience dealing with various modifications of the applications of EM monitoring. Sometimes, EM fields of internal origin in different frequency ranges are measured, sometimes a variation of geoelectrical sections is studied (Sobolev, 1995). But unfortunately, both types of EM monitoring were applied separately. They provide, however, independent information on geodynamic processes. We are currently designing low frequency modifications of such monitoring which can provide information on both types of seismo-electrical phenomena. The basic rationale is conceived as a continuous measurement of five components of the magnetotelluric field.

2. The problem statement and data processing

The MT field components, recorded at some points on the Earth surface, are mutually connected in the time domain by the relations:

$$\begin{aligned} E_x(t) &= Z_{xx}(t) * H_x(t) + Z_{xy}(t) * H_y(t) \\ E_y(t) &= Z_{yx}(t) * H_x(t) + Z_{yy}(t) * H_y(t) \\ H_z(t) &= I_{zx}(t) * H_x(t) + I_{zy}(t) * H_y(t). \end{aligned} \tag{2.1}$$

Here $H_x(t)$, $H_y(t)$, $H_z(t)$, $E_x(t)$, $E_y(t)$ are the time varying magnetic and electric components, respectively; $Z_{xx}(t)$, $Z_{xy}(t)$, $Z_{yx}(t)$, $Z_{yy}(t)$, $I_{zx}(t)$, $I_{zy}(t)$ are impulse responses of the impedance tensor $\hat{Z}$ and of the induction vector $\vec{I}$ components, respectively; the sign $*$ means a convolution. For instance, the first relation in (2.1) is a vector integral equation of convolution, with respect to the unknown impulse responses $Z_{xx}(t)$ and $Z_{xy}(t)$:

$$E_x(t) = \int_0^\infty Z_{xx}(\tau) \cdot H_x(t-\tau)\, d\tau + \int_0^\infty Z_{xy}(\tau) \cdot H_y(t-\tau)\, d\tau. \tag{2.2}$$

Usually, when performing an MT sounding such an equation is solved by transforming it into the frequency domain. We believe, however, that during continuous monitoring it is more effective to process and to interpret the data directly in the time domain (Svetov and Shimelevich, 1988). A similar opinion is expressed in the paper (Meloni *et al.*, 1996). Such an approach excludes an operation of Fourier transform and applies adaptive data processing methods, which allow data processing in a quasireal time. But in reality we have to take into account that transfer functions (impulse responses) of MT field vary with changes in the geoelectrical section and the current system in the ionosphere. Moreover, besides MT fields, there are EM fields of internal (geodynamic) origin. Therefore it is more correct to analyze a comparatively more complex equation:

$$E_x(t) = \int_0^\infty Z_{xx}(t, \tau) \cdot H_x(t-\tau)\, d\tau + \int_0^\infty Z_{xy}(t, \tau) \cdot H_y(t-\tau)\, d\tau + \Delta E_x(t). \tag{2.3}$$

The notation $Z(t, \tau)$ emphasizes the possibility of the transfer function variation with time of observation, while the term $\Delta E_x(t)$ accounts for some eventual additional anomalous field with respect to the MT one, that also includes the electrical field of internal origin. Evidently, such eq. (2.3) does not have a unique solution. It can be solved by assuming that the transfer function changes are much slower than the EM field variations. After digitization of the functions, the problem is reduced to solving a redundant system of linear algebraic equations (SLAE). In the Russian literature, the usual method for solving such a system is a minimization of the smoothing square functional formerly suggested by Tikhonov (Tikhonov and Arsenin, 1977):

$$M^\alpha\left(\vec{Z}, \vec{E}\right) = \left\|\hat{H} \cdot \vec{Z} \cdot \Delta t - \vec{E}_x\right\| + \alpha \left\|\vec{Z}\right\|. \tag{2.4}$$

Here $\hat{H}$ is a matrix of SLAE coefficients (values of horizontal magnetic field at some given sequence of time instants), $\vec{E}_x$ is a column-vector of electric filed values recorded at some given sequence of time instants, $\vec{Z}$ is a column-vector of unknown values of the impedance impulse response within a sequence of time delays, α is some regularization parameter and Δt is a sampling-step of data. The unknown transfer functions can be found by the formula:

$$\vec{Z} = \left(\hat{H}^T \cdot \hat{H} \cdot \Delta t + \alpha \cdot \hat{I}\right)^{-1} \cdot \hat{H}^T \cdot \vec{E}_x. \quad (2.5)$$

Here $\hat{H}^T$ is a transposed matrix $\hat{H}$ and $\hat{I}$ is the identity matrix. After calculating Z, one can evaluate the synthesized (predicted) electric field $\vec{E}_{xs}$, by a convolution of the horizontal magnetic field with the computed transfer functions:

$$\vec{E}_{xs} = \hat{H} \cdot \vec{Z} \cdot \Delta t. \quad (2.6)$$

The anomalous (residual) field is a difference between the total (the measured) field $\vec{E}_x$, and the predicted $\vec{E}_{xs}$ one:

$$\Delta \vec{E}_x = \vec{E}_x - \vec{E}_{xs}. \quad (2.7)$$

From our viewpoint, however, iterative methods of solving SLAE appear better suited for the monitoring problem. They can be used in adaptive methods of data processing, and allow the data to be renewed at every step of the iteration (Widrow and Sterns, 1985). After a number of iterations the computed transfer function reaches a small vicinity of its exact value and following iterations only correct the function slighthy in accordance with the new variations of the MT field components. It is convenient to present the adaptive algorithm for data processing by means of the scheme in fig. 1. The scheme has 3 inputs and 2 outputs. Horizontal components of magnetic field H_x and H_y play a role of reference signals and enter two reference inputs and a component to be processed (*e.g.*, electric component E_x) enters the main input. The components H_x and H_y are convoluted with impulse responses $Z_{xx}(\tau)$ and $Z_{xy}(\tau)$ respectively. In a discrete form each of the convolutions is expressed by the formula:

$$E_{xs}(k) = \sum_{l=1}^{L} Z(k, l) \cdot H(k-l) \cdot \Delta t. \quad (2.8)$$

Here k and l mean sampled values of t and τ in eq. (2.3) and L is a length of the impulse response $Z(k, l)$ expressed in Δt values. Then both of the convolutions are added together and the sum is compared with the signal on the main input (E_x). As a preliminary the processed data

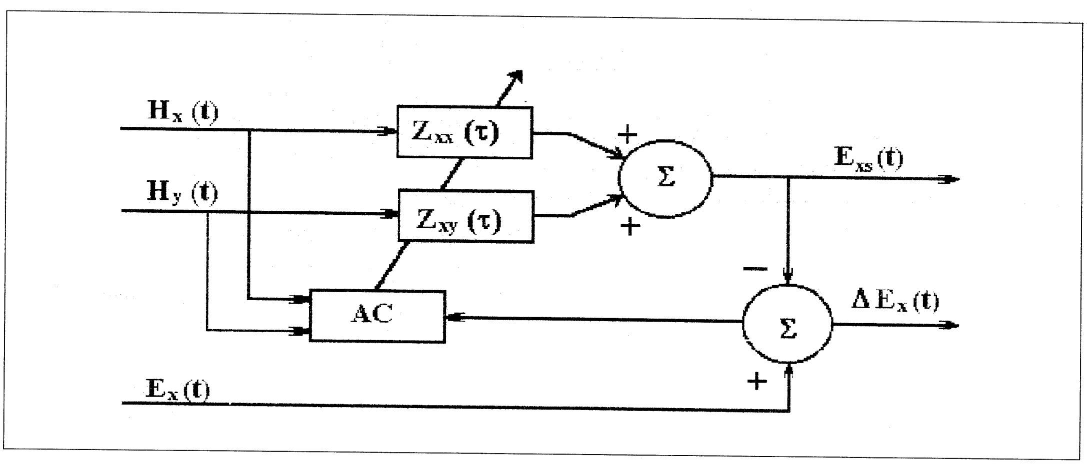

Fig. 1. The scheme of adaptive data processing algorithm.

are to be filtered in a frequency band-pass with $f_{max}/f_{min} \leq 100 \div 300$. The algorithm for correction (AC) of the transfer function values is based on the iterative least square method (Widrow and Stearns, 1985). For eq. (2.3) it can be written in the form:

$$Z_{xx}(k+1, l) = Z_{xx}(k, l) + 2\mu \cdot \Delta E_x(k) \cdot H_x(k-l)$$
$$(2.9)$$
$$Z_{xy}(k+1, l) = Z_{xy}(k, l) + 2\mu \cdot \Delta E_x(k) \cdot H_y(k-l)$$

where μ is the parameter of convergence. It is shown that the algorithm (2.9) converges if $0 < \mu < \frac{1}{(L+1)W}$, where W is the greatest power of the two processes H_x and H_y. Practically the constant μ is evaluated empirically in these limits in dependence on the type of variations and on their spectrum. Two output signals are the predicted field $\vec{E}_{xs}$ and the anomalous one ($\Delta \vec{E}_x$). Such an algorithm can be realized in a real time data-processing program. At present the program package is done for data processing in quasireal time.

3. Results of MT monitoring

Continuous observations of 5 MT field components were carried out during 1993 at one of the seismological stations on the Tien Shan mountains (Kirgizia) with a time sampling-step equal to 10 s. Some results are shown here below for the period band 20 s-1 h.

Figure 2 shows a one day (27.10.93) output of data processing for vertical components of

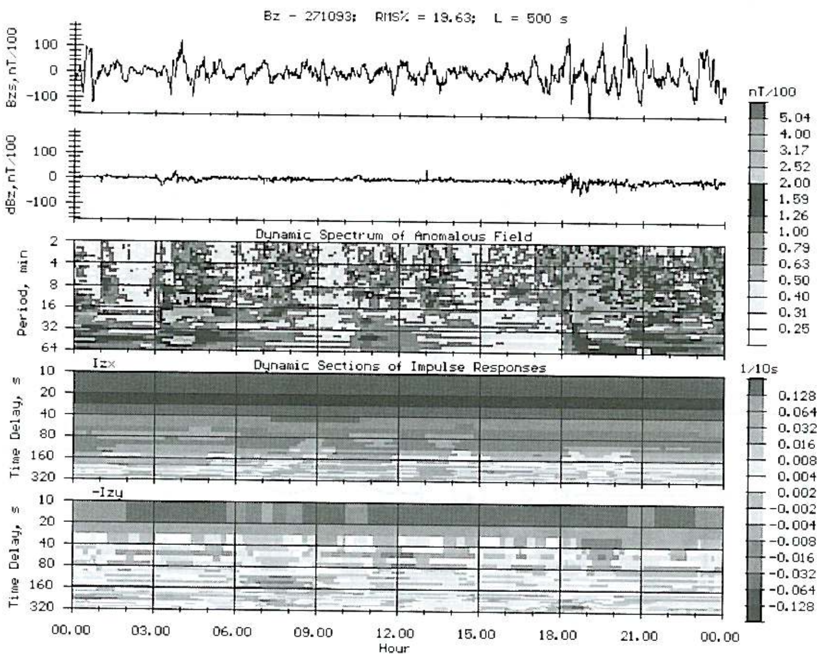

Fig. 2. Pattern of magnetic field data processing for a quiet day – anomalous magnetic field and components of induction vector. The inscription B_z 27.10.93; RMS% = 19.63, L = 500 s denotes the component of MT field, the date of observation, the relative RMS value of the residual field in percents and the length of impulse response in seconds.

magnetic field B_z. In its upper part the graphs both of the predicted B_{zs} of the residual (anomalous) dB_z field variations are represented. As a first approximation, they reflect variations of the external (MT) and internal (geodynamic) EM fields respectively. As follows from the latter graph in such a case the external MT field is well attenuated in dB_z, the relative root-mean-square value of the anomalous field to the predicted one (RMS%) is equal to 19.6%. Below these graphs a spectral-time diagram of the anomalous field is shown. It permits the information contained in the anomalous field to be represented in a more expressive form. On the diagram the time t of observation is along the horizontal axis, while the period of the residual field in minutes is along the vertical axis. The gray scale denotes the spectral density of the residual field. On the plot one can see some well-defined anomalies of the residual field. The lowest part of the picture shows the so-called dynamic sections of impulse responses of induction vector components I_{zx} and I_{zy}. On such sections time delay τ of impulse responses I_{zx} and I_{zy} in seconds is along the vertical axis and the gray scale denotes a magnitude of the impulse responses. The direction of τ-axis corresponds to a rise in the depth of investigations with increasing time delay. From such a plot, we can infer how much the transfer functions vary in time, and consequently how much the geoelectrical section changes. In this case the changes in geoelectrical section are not great. The values of impulse responses of transfer functions as well as of spectral density of an anomalous field are computed at every sampling-step, then they are averaged within 6 min intervals and are output on the plots.

The next picture (fig. 3) is another daily pattern (16.07.93) for the vertical magnetic field. In this case the relative value of residual field is higher (RMS% = 56.1) and there is a well-defined anomaly on the dynamic section of the inductive vector component I_{zy}. The anomaly of the spectral density is not so expressive in this case. Figure 4 shows a pattern (27.10.93) of electric field processing for a relatively quiet day. Here RMS% = 24.7 and the impulse responses of impedance tensor elements change slightly. In contrast, the daily pattern on 07.10.93 is an example of disturbed anomalous electric field (fig. 5). The impedance impulse responses change to a great extent, in particular Z_{xx} and the level of the anomalous field increases up to 89.2%. In general, the quality of the electric field measurement and processing is worse than for the magnetic field. It is a result of a stronger interference in this case. It is important that in all the above-mentioned cases the residual field is not correlated with the predicted one and consequently it has other sources. But it cannot be reliably declared to be of internal (seismo-electrical) origin and to be connected only with geodynamic processes. Often it can also be of local industrial origin.

After averaging of the data on 3 h intervals the daily outputs of data processing are then synthesized into monthy plots. Figure 6 is one such example for the vertical component of a magnetic field (for November, 1993). The graphs for both predicted and anomalous fields in this case are represented in the form of their intensity envelopes. As in the case of daily patterns the residual field is not correlated with the predicted one, and consequently it provides independent information. This picture also shows how the transfer functions change during longer periods of time.

Figure 7 is the same monthly plot but for the electric field. Both anomalous field, and impedance transfer functions appear much more disturbed than in the case of the magnetic field. Here the level of residual field is equal to 49.4% and there are pronounced anomalies of impedance impulse responses. Its duration is about several days. A special feature of the monthly patterns is that the anomalous field involves a pronounced daily harmonic. It is clearly seen on the graphs of the residual field and on its spectral-time diagrams (especially in the electric field). Since the data are presented in the period band 20 s-1 h, such a phenomenon may be the result of field modulation only.

After 1 day averaging of 3 h sampling data the monthly outputs of data processing are synthesized into a yearly plot. Figure 8 is an ex-

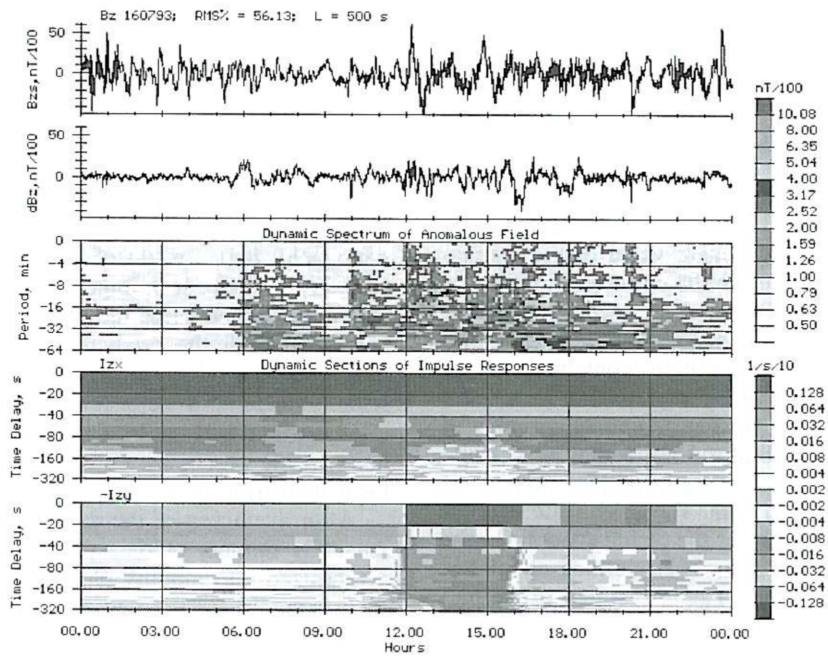

Fig. 3. Pattern of magnetic field data processing for a disturbed day (16.07.93).

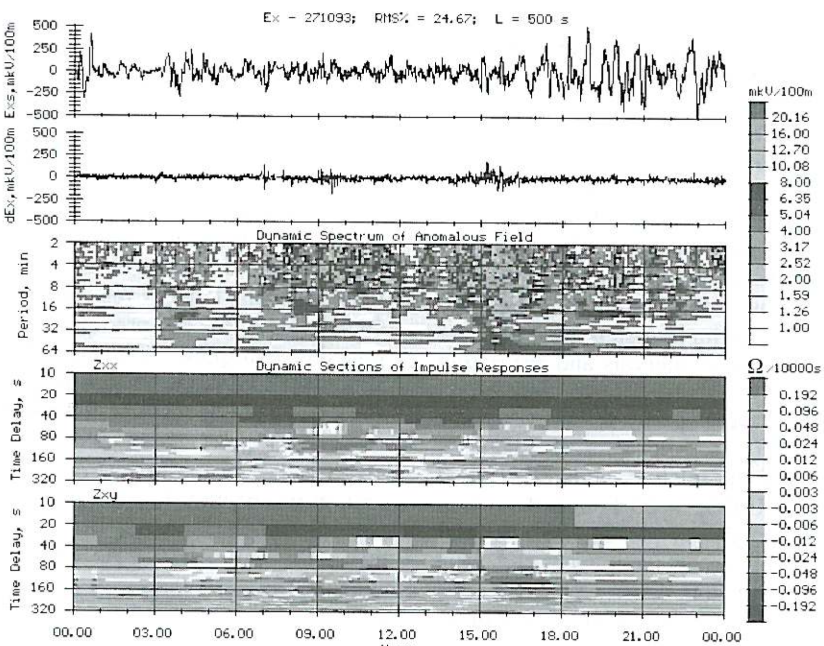

Fig. 4. Pattern of electric field data processing for a quiet day – anomalous electric field and components of impedance tensor (27.10.93).

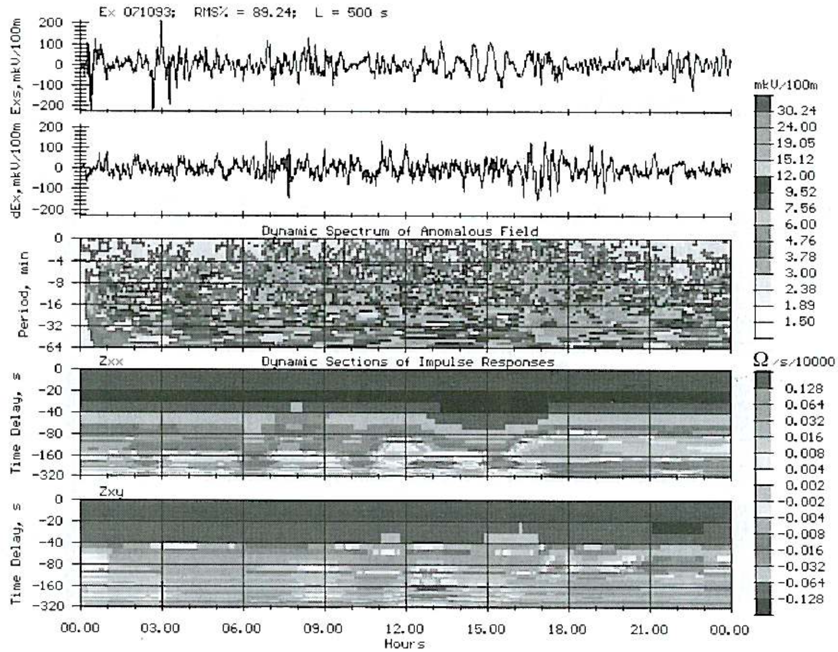

Fig. 5. Pattern of electric field data processing for a disturbed day (07.10.93).

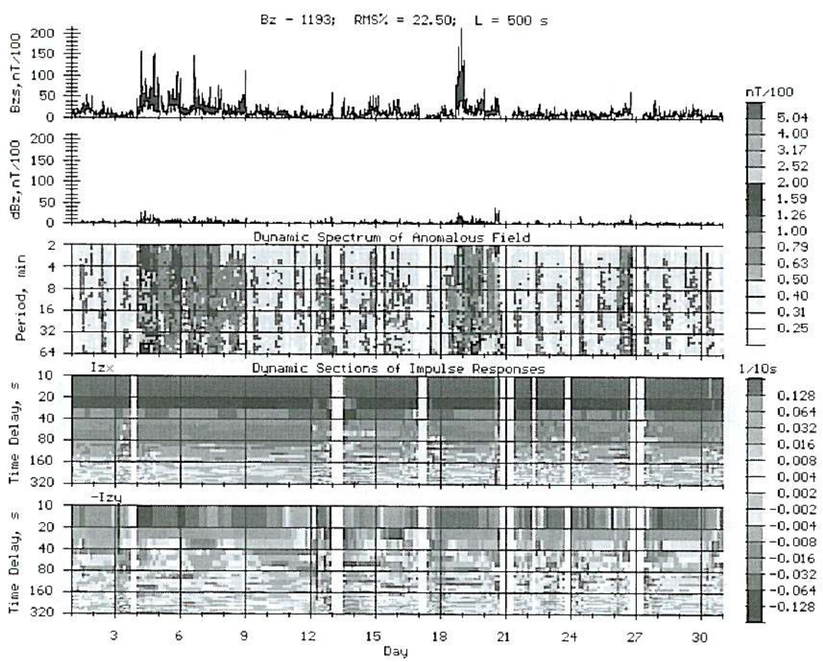

Fig. 6. An example of a monthly plot for the magnetic field after averaging the daily plots (11.93).

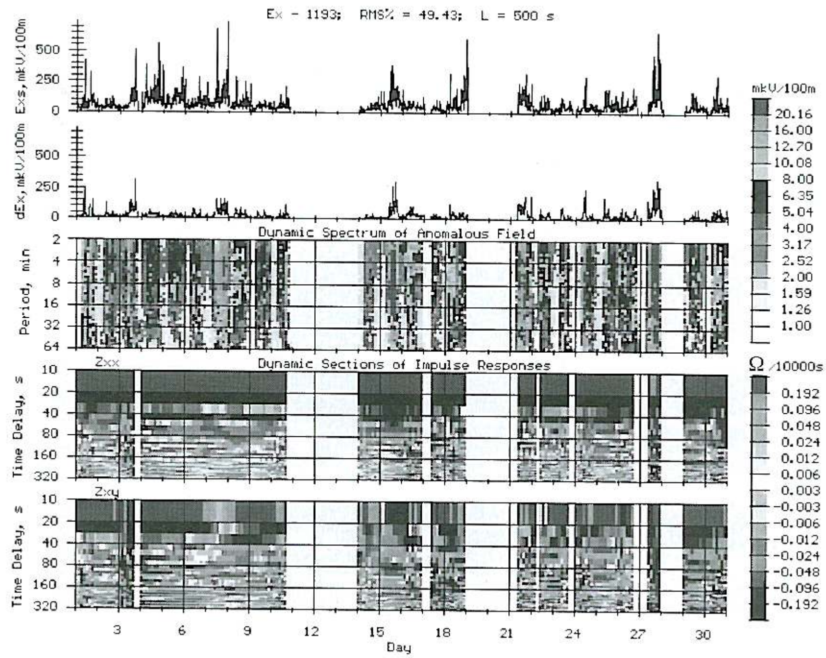

Fig. 7. An example of electric field monthly plot (11.93).

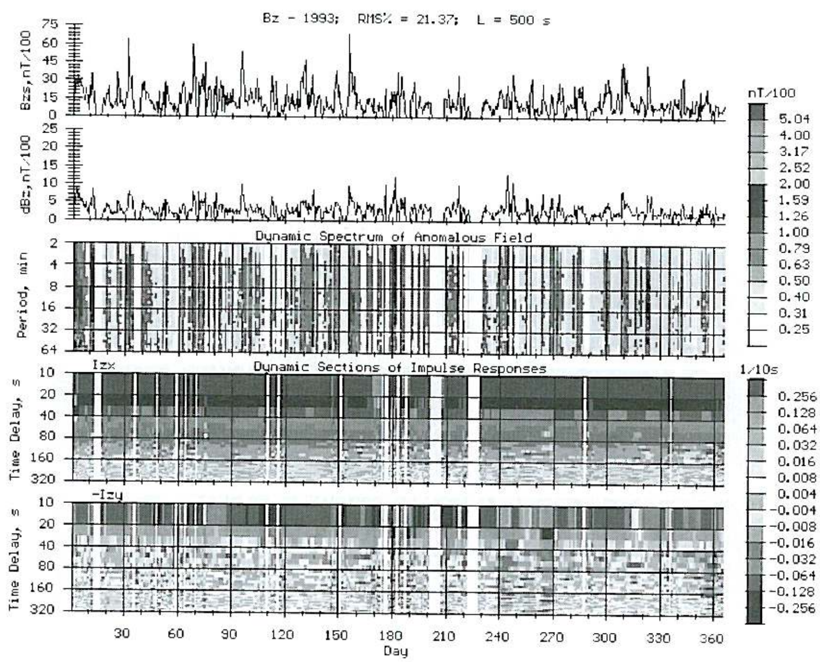

Fig. 8. Pattern of a yearly plot for the magnetic field (1993).

ample of such plots for the vertical magnetic field. The plot of the anomalous field does not appear expressive in such a form. Concerning the dynamic sections of the transfer functions, they show some anomalous zones. At present, their origin as well as the origin of anomalies on daily and monthly plots are not clear. This is partly explained by the fact that during 1993 several weak seismic events occurred, although no powerful one. But the main cause is connected with the fact that the MT field observations were performed at one station only. Therefore, we cannot reliably interpret the observed disturbances of the residual field and of the transfer functions and locate a position of their source. For the same reason no trustworthy judgements can be made on the correlation between EM disturbances and seismic events. For a reliable interpretation of the MT monitoring it appears essential to record simultaneously the EM field at several stations, and to correlate EM observations with other geophysical parameters.

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