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Induction Sounding of the Earth's Mantle at a New Russian Geophysical Observatory

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Abstract

Deep magnetotelluric (MT) sounding data were collected and processed in the western part of the East European Craton (EEC). The MT sounding results correspond well with impedances obtained by magnetovariation (MV) sounding on the new geophysical observatory situated not far from the western border of Russia. Inversion based on combined data of both induction soundings let us evaluate geoelectrical structure of the Earth's crust and upper and mid-mantle at depths up to 2000 km, taking into account the harmonics of 11-year variations. Results obtained by different authors and methods are compared with similar investigations on the EEC such as international projects CEMES in Central Europe and BEAR in Fennoscandia.

Key words: mantle, geoelectrical structure, East European Craton.

1. INTRODUCTION

By the late 2011, 35 European geomagnetic observatories have been registered in the International Real Time Magnetic Observatory Network (INTERMAGNET). Only one of these, Borok (58°04′ N, 38°14′ E), is operating in the European part of Russia (Anisimov *et al.* 2008). It is evident that the development of geophysical observatories in Russia is important for the international community to investigate the Earth's crust and mantle, for ex-

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ample, by monitoring the physical fields. The Aleksandrovka Observatory belongs to the geophysical base of the Moscow University (250 km to the south-west of Moscow) which has been under construction since 2006. The place is poorly populated; there are no other settlements within a radius of 8 km and the distance to the nearest DC electrified railway is over 50 km, thus ensuring a low level of industrial noise. The settlement is electrified and the base is provided with diesel-generator emergency electric power. Internet communication is supported by two-way (GPS/GLONASS) satellite systems. The non-magnetic pavilion construction has been completed (54°53′79″ N and 35°00′87″ E) and geophysical data have been collected since May 2011. The purpose of the Observatory is to measure the full vector of the Earth's magnetic field (LEMI 025 fluxgate magnetometer; Korepanov *et al.* 1998), and to carry out uninterrupted recording of variations in horizontal components of the electric field (Shustov *et al.* 2012). Seismological three-component measurement stations were also installed. We hope to install proton magnetometer for absolute values of magnetic field measurement in the nearest future.

2. THEORETICAL BASE

The impedance is the basis of induction soundings. It was introduced by Leontovich in Russia at the beginning of 1930s (Rytov 1940). The strict theory of radio-waves spreading in the medium was developed by Rytov, who was Leontovich's follower (see Senior and Volakis 1995). Induction soundings were put into practice using equations for the first term of series. They were obtained for the boundary between isolated and conductive media. The impedance was considered as a scalar, or strictly speaking the functional of conductivity distribution via skin depth (Rikitake 1948, Tikhonov 1950, Cagniard 1953). Today, the impedance is a matrix that is formed by anisotropy or heterogeneity of the medium. It was introduced by Berdichevsky and Cantwell (see Berdichevsky and Dmitriev 2008). Equations for magnetotelluric (MT) and generalized magnetovariation (GMV) soundings are as follows:

$$\begin{aligned} E_x(\omega) &= Z_{xx}(\omega)B_x(\omega) + Z_{xy}(\omega)B_y(\omega), \\ E_y(\omega) &= Z_{yx}(\omega)B_x(\omega) + Z_{yy}(\omega)B_y(\omega), \\ B_x(\omega) &= Y_{xx}(\omega)E_x(\omega) + Y_{xy}(\omega)E_y(\omega), \\ B_y(\omega) &= Y_{yx}(\omega)E_x(\omega) + Y_{yy}(\omega)E_y(\omega), \end{aligned} \tag{1}$$

$$B_z(\omega) \approx C(\omega, r)\,\mathrm{div}\,B_\tau(\omega) + \mathrm{grad}\,C(\omega, r)\,B_\tau(\omega)\,. \tag{1a}$$

Here $C(\omega, r)$ is a response function in GMV sounding method, where r is a radius vector. It is transformed into apparent resistivity in SI with the formula: $\rho^* = i\omega\mu_0 C^2$ where i is the imaginary unit, $\mu_0 = 4\pi 10^{-7}$ [Henry/m] the permeability of the free space, $\omega = 2\pi/T$ the circular frequency and T-the period. The laconic Eq. 1a was formulated by Guglielmi and Gokhberg (1987), and Schmucker (2003). A more precise theory was presented by Shuman and Kulik (2002), and Shuman (2007) (see Semenov and Shuman 2010). The complex Fourier amplitudes for the corresponding components of MT field, B_τ, E_x, E_y, B_x, B_y, B_z, are connected through matrices of impedance $||Z||$ and admittance $||Y||$:

$$Z = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}, \quad Y = \begin{pmatrix} Y_{xx} & Y_{xy} \\ Y_{yx} & Y_{yy} \end{pmatrix}. \tag{2}$$

For an isotropic horizontal uniform medium, grad $C = 0$ (components of this vector on the x and y axis are different from tippers). The Eq. 1a can be transformed to the equality $B_z(\omega) \approx C(\omega, r)$ div $B_\tau(\omega)$, which was introduced for MV soundings by Berdichevsky *et al.* (1969) and Schmucker (1970). It can be simplified for *Dst* variations, because the field induced by ring currents in the magnetosphere is linearly polarized in the Earth (Olsen 1998). This field is sufficient for defining the Earth response function (Banks 1969):

$$i\omega B_r(\omega) = C(\omega, r)\frac{2B_\theta(\omega)}{R\,\mu_0 tg\left(\theta_0\right)}. \tag{3}$$

Here R is the Earth's radius, θ_0 the geomagnetic colatitude of observation place, and B_r, B_θ the spectra of radial and colatitude components of the magnetic field. Equation 3 is valid in geomagnetic coordinate system on the sphere.

If all the elements of impedance matrix are found and $Z_{xx} \equiv Z_{yy} = 0$, $Z_{xy} = Z_{yx} = Z$ regardless of the direction (uncommon case in practice), the conductive medium can be presented as uniform, isotropic halfspace with one scalar impedance $Z(\omega)$. It is transformed to the scalar resistivity as follows

$$\rho = \frac{\mu_0 Z^2}{\omega}. \tag{4}$$

In a more common case, $Z_{xy} \neq Z_{yx}$ and additional impedances are nonzero. Then we have a non isotropic medium. In the best case it can be described by tangential anisotropic uniform halfspace. Its resistivity is defined by plate tensor. Components of apparent resistivity tensor can be found by the following expressions (Eq. 5), which were obtained theoretically from Maxwell equations by Reilly (1979) (see Weckmann *et al.* 2003) and Semenov (2000):

$$\begin{gathered}\rho_{xx} = \mu_0\left(Z_{xy}^2 - Z_{xx}Z_{yy}\right)\Big/\omega\,, \quad \rho_{xy} = \mu_0 Z_{xx}\left(Z_{yx} - Z_{xy}\right)\Big/\omega\,, \\ \rho_{yx} = \mu_0 Z_{yy}\left(Z_{xy} - Z_{yx}\right)\Big/\omega\,, \quad \rho_{yy} = \mu_0\left(Z_{yx}^2 - Z_{xx}Z_{yy}\right)\Big/\omega\,. \end{gathered} \tag{5}$$

Effective apparent resistivity is used for heterogeneous media. It is usually defined from polar diagrams of impedance or admittance matrixes. However, you can quite easily localize the heterogeneity place by examining the effective apparent resistivity. It can be calculated by using the generally accepted formula, without guidance of possible heterogeneity degree:

$$\rho_{\text{eff}} = \mu_0\left(Z_{xx}Z_{yy} - Z_{xy}Z_{yx}\right)\Big/\omega\,. \tag{6}$$

This approach is well applicable during anomalous conductivity zones searching in exploration geophysics. But it is inadmissible during deep Earth's research because of the lack of proven data (drilling is well proven data for exploration geophysics).

Model with horizontal anisotropy is worth to be considered for conductive structure definition of the Earth's mantle. Its anomalous zones are local. It can be modeled by stratified, anisotropic structure in regional scale.

3. DATA PROCESSING

Processing of MT data leads to defining the elements of MT matrix (Berdichevsky and Dmitriev 2008), *i.e.*, two unknowns from one of Eqs. 1.

In the GMV sounding case (Eq. 1a) the number of unknowns increases to three at least: scalar impedance and two tippers. Such a decision can be evaluated just under the assumption that the number of process realizations is big enough, for example, in the context of the theory of stochastic processes.

The obtained values have a stochastic character and so are characterized by confidence intervals under the assumption that displacement errors (bias), which depend on noises, are small. This is indicated by the corresponding coherencies (Reddy and Rankin 1974). There is a method to avoid bias by correlation of all observed data with similar data in a remote point (Gamble *et al.* 1979).

There are a lot of algorithms for defining $||Z||$ and $||Y||$ matrices by records of MT field. For example, one method is based on narrow band digital filtration (Narsky 1994, Berdichevsky and Dmitriev 2002), another one is based on classical method of spectral analysis (Sims *et al.* 1971), and a third one analyzes data in time domain (Nowożyński 2004). There is an interesting fact. The theory is constructed for a single frequency but impedances often characterize a certain band. It is also a set of realizations but for neighbouring frequencies.

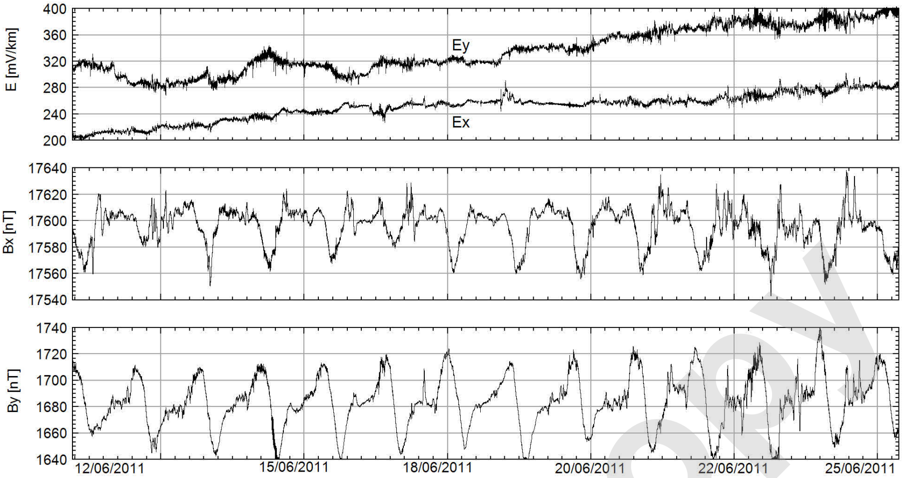

Fig. 1. An example of 15-day interval of MT field registered on the Aleksandrovka Observatory in June 2011. B_x and B_y are the components of magnetic induction vector, x the direction to the geographical north, y to the east, E_x and E_y are the components of electric field; the length of receiving lines is 100 m.

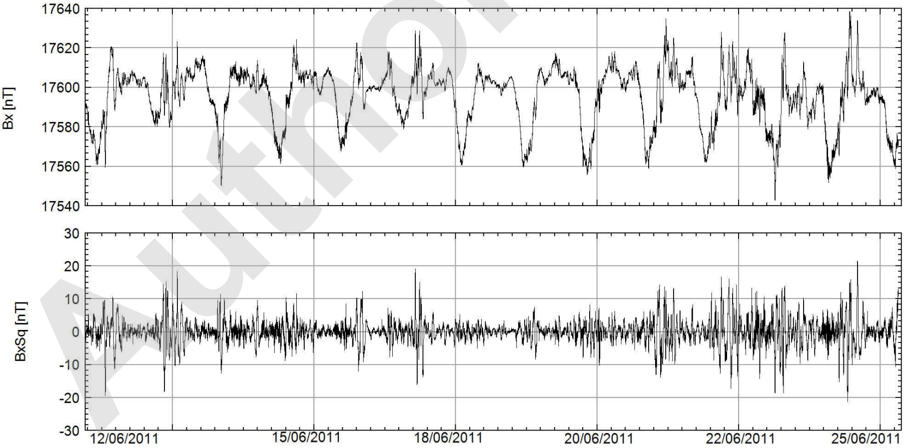

Fig. 2. Removing diurnal variations on the example of 15-days record on Alexandrovka base in June 2011 (B_x – component of the magnetic field, B_{xSq} – filtration result).

The MT data chosen for analysis were obtained in summer 2011. Some part of these data is presented in Fig. 1. While defining impedances it is necessary to switch from Eq. 1 for monochromatic electromagnetic wave to a continuous distribution of spectral frequency. Spectral distributions of field components let the required functions values with their casual errors and bias (it is often higher than casual errors). The coherence defines reliability of implementation of Eqs. 1, 1a for real data (Semenov 2000).

For a long period, the data processing was performed by using the Petrischev/Tkachev program (Method 1, Semenov 1985). Processing scheme of MT-data in this method includes removing short-term spikes with a nonlinear filter (Naudy and Dreyer 1968), removing diurnal harmonics of observed field (Fig. 2) (Parkinson 1983) and, finally, selection of data with high coherency, *i.e.*, less distorted sections with noises.

It is worth noting that the main directions for different periods are different. Three sections were selected. The main direction was selected to be 150 degrees for the first section, $T \in [30, 2500]$ s; 170 degrees for the second section, $T \in [2500, 8000]$ s; and 150 degrees (the same as at the first one) for the third section, $T \in [8000, 25\,000]$ s (Fig. 3). The second processing stage includes analyzing the whole record with the selected main direction. Different displacement windows are chosen. This window is charged with the length of data for the fast Fourier transform.

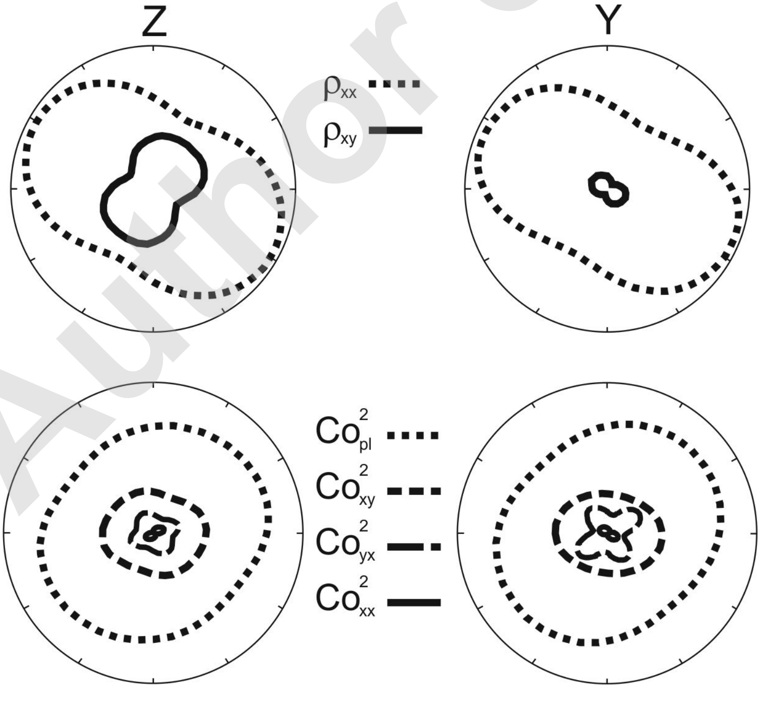

Fig. 3. Polar diagrams of primary and additional components of apparent resistivity tensor [Ohm·m] (upper image) and square coherencies: Co^2_{pl} – plural, Co^2_{xy}, Co^2_{yx} – singular, Co^2_{xx} – input signals (bottom), received for impedance *Z* (left) and admittance *Y* (right) estimations for $T = 10\,000$ s.

The observed data were processed by different algorithms. The first method was used for processing just on the Aleksandrovka Observatory. Varentsov's algorithm (Method 2) was used in multi reference scheme. It is formed on robust averaging of estimates for several base points. Also, there were some boundary conditions on horizontal MV response changes between investigation point and remote bases (Varentsov 2007).

Additional MT and Audio-MT three-day's data were added to the joint process by Varentsov's and Larsen's algorithms (Larsen *et al.* 1996) (Method 3).

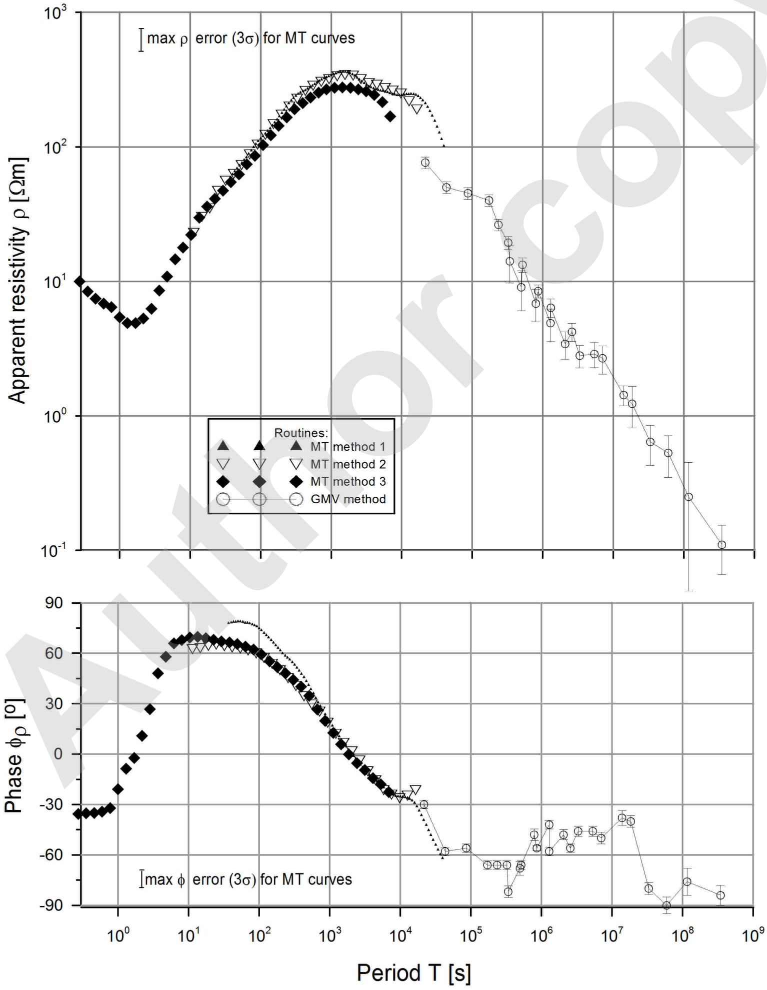

Fig. 4. Complex apparent resistivities of central part of the EEC estimated by three independent MT routines at the Aleksandrovka Observatory and GMV method at the Moscow Observatory.

4. COMPARISON OF PROCESSING RESULTS

Method 1 does not take into account frequency characteristics of the equipment. Results obtained by this algorithm differ from the Varentsov's and Larsen's algorithms in low period area (Fig. 4). It is necessary to consider frequency characteristics of the equipment for the period range lower than 600 s ($T < 6000$ s). Reliability of acquired data was improved using several base stations and robust averaging procedure. This is well seen especially in the long period area ($T > 6000$ s). The results of different processing are well corresponding up to the period of $T \approx 3$ hours ($T = 10^4$ s). Then serious discrepancies occur (Semenov and Shuman 2010, Shimizu *et al.* 2011). Three kinds of source fields are dominant at the period range 10^4-10^5 s daily oscillations (*Sq* variations) connected with the Earth's rotation, bays caused by polar cusp currents, and *Dst* variations caused by the magnetospheric ring current. The bays can be considered as a plane wave (Vanyan *et al.* 2002) with the vertical magnetic component in the middle latitudes, while the *Dst* variations contain the stable magnetic field which is collinear with geomagnetic axis (Banks 1981, Fujii and Shultz 2002). However, the MT soundings can be replaced by GMV soundings for the periods of 3-30 hours (Semenov *et al.* 2011). The data of Moscow Observatory (CEMES project, Semenov *et al.* 2008) were used for those purposes (Fig. 4).

5. THE INVERSION

First of all, the phase inversion of the impedance was accomplished by OCCAM algorithm (Constable *et al.* 1987). Thus, the module of apparent resistivity tensor was corrected for surface heterogeneity obtained by MT data (Fig. 5).

Inversions by the well-known OCCAM and D+ algorithms were held for corrected responses of MT and GMV methods. D+ let us create geoelectrical horizontal layered media. Conductive layers approximate by thin layers with finite conductance (Parker 1980).

Sediments, crust, asthenosphere, and mid-mantle layer were picked out during 1D interpretation (Fig. 6a). The sediments of Moscow syncline have a thickness of 800 m.

The upper boundary of asthenosphere was picked out at a depth of 280 km. The upper boundary of the mid-mantle layer is at a depth of 660 km. The D+ results are quite representative. The upper boundary of the asthenosphere has a depth of 230 km. The mid-mantle layer has its edges at depths of 670 and 900 km. Additional conductive layer was picked out by the D+ algorithm. It has the conductance of 160 S at a depth of 65 km. We think this layer can be the appearance of the conductive layers of the lower crust. They should be shallower. We used previous investigations for evalua-

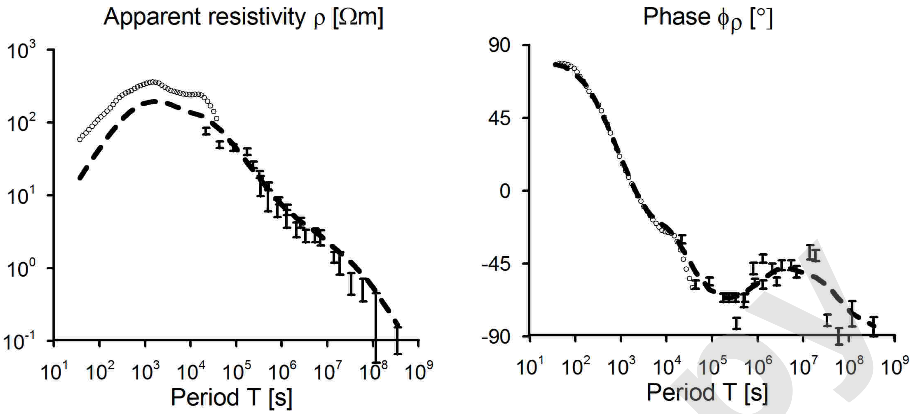

Fig. 5. The correction result obtained by OCCAM (dashed black) algorithm. Complex apparent resistivities estimated by the MT method for Aleksandrovka are shown as empty points and the MV method for the Moscow Observatory are shown as error bars.

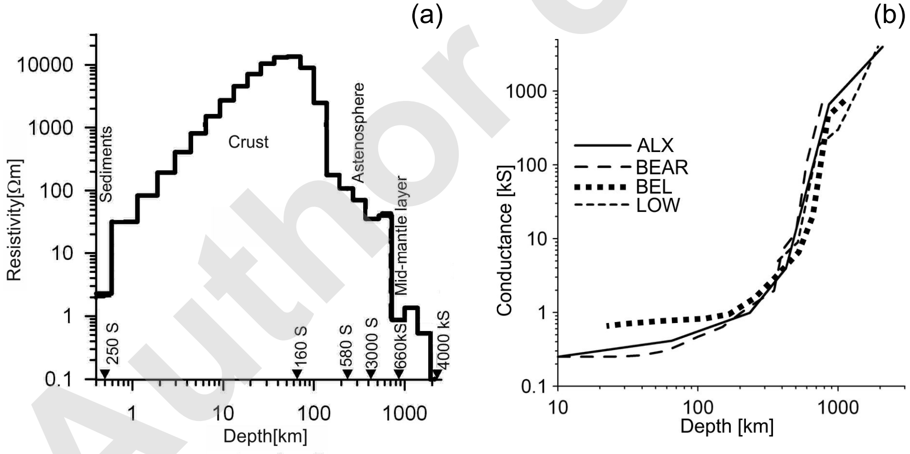

Fig. 6. Comparison of inversion results of MT and MV data for Aleksandrovka and Moscow Observatories; solid line is the OCCAM decision, arrows show D+ thin layers with their conductance (left panel) and conductance comparison obtained on different observatories. ALX – Aleksandrovka Observatory, BEAR – Fennoscandian experiment (Varentsov *et al.* 2002, Sokolova and Varentsov 2007), BEL – observatory in Poland, LOW – observatory in Sweden. Data from two last observatories were obtained during CEMES project (Semenov and Jozwiak 2006, Semenov *et al.* 2008).

tion of the obtained results. These were the BEAR project, based on data obtained in Fennoscandian region, and CEMES in the central part of Europe.

The comparison was carried out by the curves of integral conductance (Fig. 6b). The choice was made of the S curves. Each conductivity distribution corresponds with the one conductance value. So the uniqueness theorem for 1D inversion is proved only for infinite frequency range.

6. RESULTS AND DISCUSSION

Aleksandrovka is a geophysical observatory of Moscow University. Long-period registration of MT-field is held here. The obtained data were processed by several authors with different algorithms, such as the only observation point processing or using several base stations. The robust estimation was used. It has become a standard procedure during MT data processing. We have got close results for $T < 10^4$ s for all researching algorithms.

For longer periods it is hard to get truthful estimations due to several reasons. Estimation procedures of transfer operators for several base stations improve processing result. The obtained results correspond well with deep geoelectrical mantle properties. Moreover, they figure on a relative homogeneity of the mantle on the EEC. The sharp increase of mantle conductivity begins with depths of 300-400 km. We think it is connected with the asthenosphere.

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