ANNALS OF GEOPHYSICS, 65, 1, GM104, 2022; doi:10.4401/ag-8751
OPEN ACCESS

Source effect impact on the magnetotelluric transfer functions

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Article history: received November 9, 2021; Accepted February 7, 2022

Abstract

It is known that the deviation from the plane wave assumption (the so-called source effect) has an impact on the results of vertical transfer function (VTF) estimation, especially for long periods. We observe the so-called seasonal effect, i.e. the VTF calculated from the data measured in the summer months is different from the VTF estimated from the winter months data. This is related to the length of the day, as in the diurnal data the effect of deviation from the plane wave is greater. In the present work, its potential effect on the estimation of the impedance tensor for magnetotelluric soundings is investigated. A unique, very long series of magnetotelluric recordings at the Belsk Magnetic Observatory was used for the analysis. The results showed that we do not observe the summer-winter seasonal changes as it is in the case of VTF. Small differences can be noticed as a result of TF estimation separately for diurnal and nocturnal data. The analysis of prediction errors confirms this finding and proves that the daily data are more distorted (distant with the plane wave). More detailed analyzes were performed by making a precise selection of data, dividing them into those that fulfill and those that do not fulfill the assumptions of the plane wave. The results show that the impedances estimated from data separated in this way may differ by several percent.

Keywords: Magnetic field; Geomagnetic induction; Magnetotellurics; Time-series analysis; Ionosphere/magnetosphere interactions.

1. Introduction

Magnetotelluric sounding is a widely used tool for studying the internal structure of the Earth. The natural changes in the geomagnetic field induce an electric current in the interior layers of the Earth. The directions and intensity of such current depend on the distribution of electrical conductivity. The relationships between the components of the electromagnetic field, measured at the Earth's surface, are functions of subsurface electrical conductivity and frequency of the sounding waves. These relationships are expressed as transfer functions (TF) and include the tipper vector T (VTF):

$$B_z = \begin{bmatrix} T_x & T_y \end{bmatrix} \cdot \begin{bmatrix} B_x \\ B_y \end{bmatrix} \tag{1}$$

and impedance tensor Z, in the matrix notation:

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \cdot \begin{bmatrix} B_x \\ B_y \end{bmatrix} \tag{2}$$

The impedance tensor Z and vertical transfer function vector T are complex functions of a position and frequency useful for the modelling of resistivity distribution [Rokityanski, 1961; Parkinson, 1962; Wiese, 1962; Tikhonov and Berdichevsky, 1966].

The above definitions are correct assuming that the primary electromagnetic field is a plane wave that propagates vertically towards the Earth's surface. It is generally accepted that in the middle geographical latitudes, where source fields are generated by large-scale electric current systems in the ionosphere, far away from observation points, the plane wave assumption is fulfilled [Simpson and Bahr 2005]. However, even there, in practice, it turns out that this assumption is not always verified. Therefore, we must bear this in mind when processing data, as a reliable estimation of the transfer function is crucial for the correct interpretation of the electromagnetic sounding results.

Of course, the assumption of a plane wave is especially important in the case of magnetovariational soundings. In formula (1) we assume that the external horizontal magnetic field induces the internal vertical component B_z. If we have a vertical component in the external field, we register both components on the Earth's surface and we have no tools to separate them. Thus, the calculation of the VTF based on formula (1) gives erroneous results.

There are many reports that the VTF estimated on the basis of data from different time periods may differ, especially for long periods (> 1500 s). VTF is a function closely related to the local conductivity distribution. Thus, changes in VTF over time would indicate changes in the geological structure. While such changes are possible in seismic regions, we also see effects in stable regions that are not seismically active. Detailed analysis explains that the observed VTF variability is the result of estimation errors due to the fact that the magnetic field variations do not satisfy the plane wave assumption; in other words, there is a non-zero vertical component in the external field that appears as correlated noise in the data set [Ernst et al., 2020; Araya Vargas and Ritter, 2016]. Tests have shown that the magnitude of the disturbance is closely related to the recording time. There is a seasonal regularity: the winter data are least disturbed, and the summer data the most disturbed (large vertical component of the external magnetic field). In the short term, the data recorded from sunset to no more than 8 hours after sunrise is clearly less distorted than the data for the rest of the day. As a result, in summer, when the day is long, we have bad seasonal data as opposed to winter when the data is least polluted almost 24 hours a day. When analyzing the estimated external parts of the vertical components in Central European observatories, we noticed a high similarity of these signals, even if the inductive components were clearly different, indicating that this is a regional effect.

This problem is not so significant in the case of magnetotelluric soundings. In formula (2), the impedances are calculated only from the horizontal components of the magnetic field. But also here, the external part of Bz variations leads to an error in the impedance estimation. The external vertical components of the magnetic field induce horizontal ring currents which disturb the correct calculation result.

In this paper, we will analyze a series of magnetotelluric measurements carried out over many months at the Belsk Magnetic Observatory, Poland (coordinates 51.837° N, 20.792° E). Firstly, the seasonal effect was analyzed by estimation of the transfer functions separately for summer and winter months using the Egbert algorithm [Egbert and Booker 1986]. It was also examined whether the result of the transfer function estimation changes if we perform calculations on the basis of day-time data only. Finally, more detailed analyzes were performed, dividing the data into those segments for which the plane wave assumption is fulfilled and those that do not fulfill this assumption. As a selection criterion, we used the difference between the recorded and the predicted (induction) component of Bz. Then we compared the result of the impedance estimation for the data sets selected in this way.

2. Data

For our considerations, we will use several-month-long series of magnetotelluric recordings at the magnetic observatory in Belsk. Recordings were performed in 2001-2002 as part of the project of deep electromagnetic induction soundings in Central and East Europe under the acronym CEMES (Central Europe Mantle geoElectrical

Structure) and joined by nine research institutes from different countries in the region. The main objective of CEMES was to study the distribution of electrical conductance in the upper mantle beneath the region, based on a joint interpretation of long-period magnetotelluric (MT) data with already available deep magnetovariation (MV) sounding results from geomagnetic observatories [Semenov et al., 2008]. Reliable magnetotelluric response estimates for the period range from several hours to one day would contain essential information about the geoelectric structure of the upper mantle. So, the quality of telluric registrations was studied with special attention to long-period signals.

It is believed that this problem is mainly related to the quality of the electrodes, although, of course, the quality and stability of the amplifiers and the quality of the cables are also important. Fortunately, the test of electric equipment for field observation in deep magnetotelluric soundings was carried out in Belsk before measurements. We made test registrations of the same electrical field measured by different types of electrodes (Ag/AgCl designed in Germany and Cu/CuSO4 designed in Poland) to estimate the accuracy of measurements, with special attention to long-period observations. For this experiment, parallel electrical dipoles, equipped with both types of electrodes, have been installed side by side on the grounds of the geomagnetic observatory Belsk. The distance between the electrodes was 185 m for each dipole and the distance between these dipoles was 3 m. All electrodes were installed at a one-meter depth. They had been surrounded by wet kaolin just before the installation into the ground. Quality cables connecting these electrodes with the amplifiers were laid on the ground and were fixed to the ground every 20 to 30 meters. To avoid the temperature effect, special telluric amplifiers with a compensation of the temperature influence were designed in Belsk. Tests have shown that the measuring system used is sufficient for a reliable recording of the electrical fields induced by daily geomagnetic variations in Central Europe [Semenov et al., 2001].

For data processing in this study we used one-minute geomagnetic variations and telluric components Ex, Ey measured on the Belsk Observatory area from June 1, 2001 to December 31, 2002. The periods longer than three hours were filtered out, using optimal filters calculated by the algorithm of Parks and McClellan [1972]. These data were used to analyze the influence of the source effect on the results of the estimation of magnetotelluric transfer functions.

3. Data analyses and results

At the beginning, we examined whether the effect of seasonality is observed in the same way as in the case of tippers [Ernst et al., 2020]. For this purpose, TF was calculated separately for the summer and winter months using the Egbert method. The results show that there are no significant differences between the TF estimates (Figure 1). This means that either the source effect has little effect on the TF estimation or the robust methods are good at eliminating the negative impact of deviation from the plane wave.

In the work of Ernst et al. [2020], it was shown that the tipper estimation result is different for day-time and night-time. This is because during the day the external field more often does not fulfill the assumption of a plane wave and we observe a vertical component in it. Also in the case of impedance, we also observe a difference in the estimation results between day and night, but it is much smaller. For the impedances estimated only on the basis of day-time data for periods in the order of 1800 s, we observe TF fluctuations shown in Figure 2.

To find out what is the cause of these differences, we performed a more precise analysis, preselecting the data to those that fulfill and do not fulfill the assumptions of the plane wave [Ernst et al., 2020]. The data selection criterion will be the verification whether the output signal is close to the inductive one, and more precisely, whether it contains variations that are not a result of induction caused by the horizontal component of the magnetic field. For this purpose, we used the predicted (induction) b_z component. The time-domain method was used to estimate the tipper [Ernst, 1981]. It does not have a built-in robust mechanism, so before the calculations, we use a specially developed application that allows for the initial selection of data. The algorithm works well for short data segments as well. Using this tool, we will separate recording segments for which the assumption of the plane wave is fulfilled from those for which this condition is not fulfilled. In the first step, the impulse response is calculated from all available data. Then, by convolving the impulse response with the input signal (horizontal component of the magnetic field) we calculate the induction component of the vertical magnetic signal. The predicted error ($\delta b_z = b_z - pb_z$) can be obtained by subtracting from the recorded b_z component their prediction calculated on the basis of tippers. The value of δb_z is useful for identifying the intervals for which the data fulfill the plane wave assumption and those for which the deviation from this assumption is the greatest (the prediction error is the

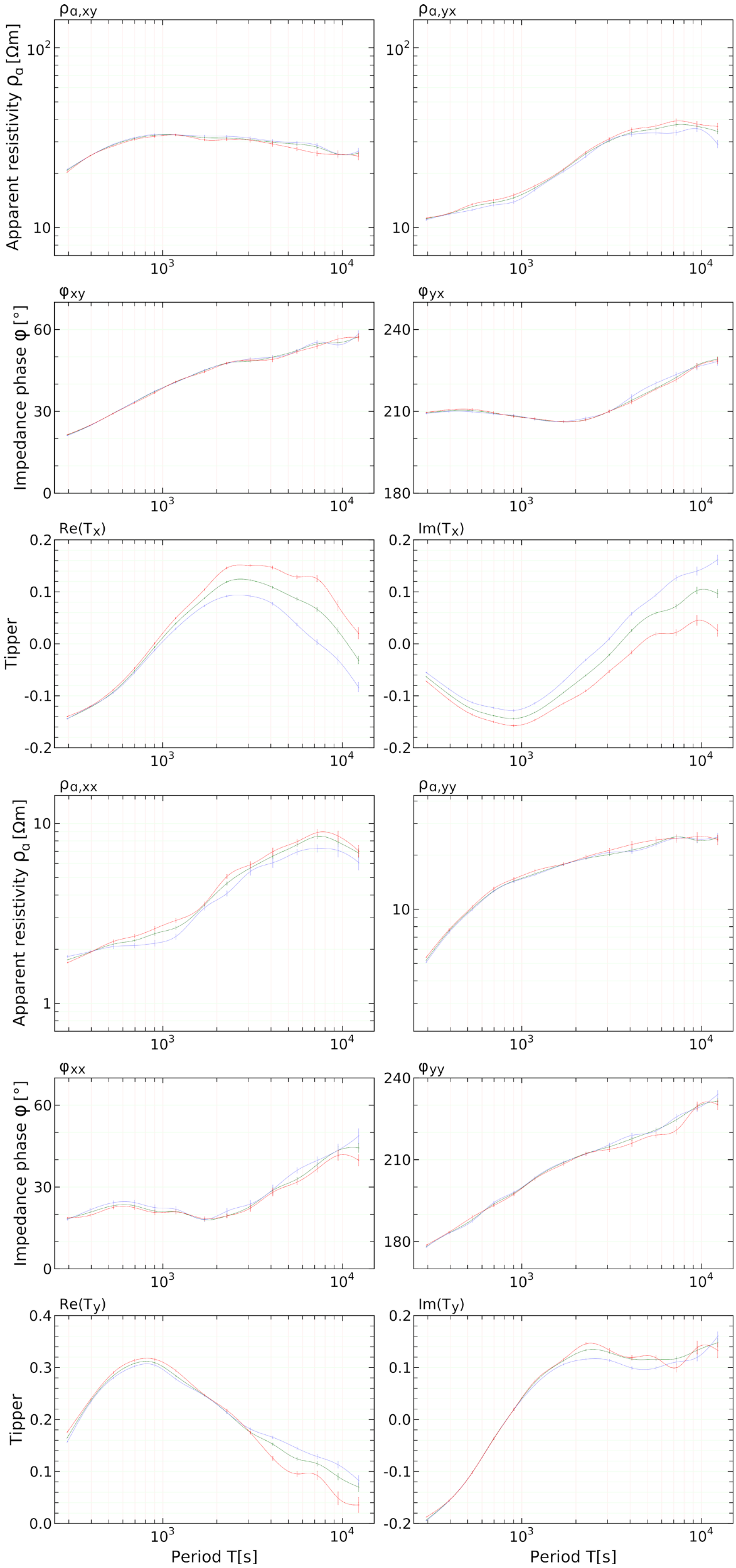

Figure 1. The result of TF estimation for summer (red), winter (blue), and all (green) data.

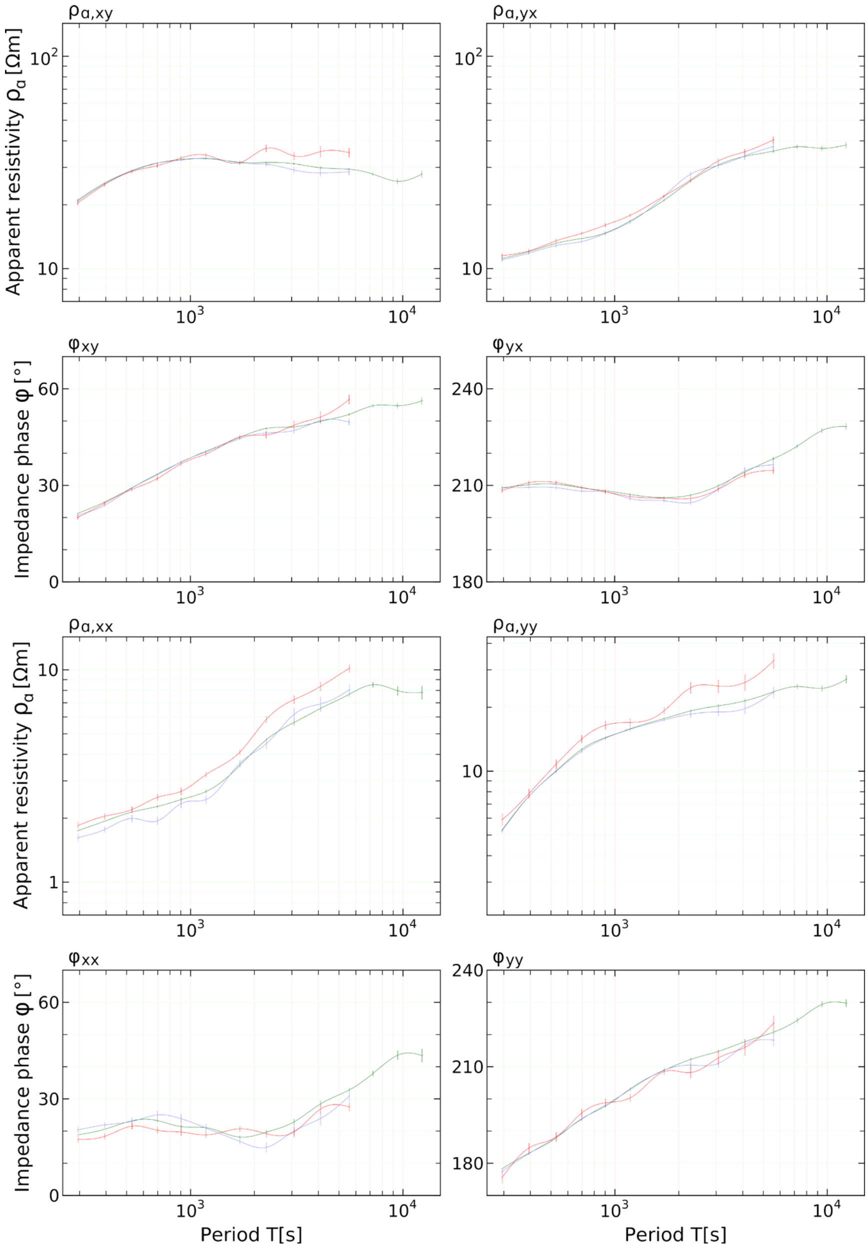

Figure 2. The result of TF estimation for day-time(red), night-time (blue), and all (green) data.

largest). The selection is based on the ratio $\delta\widehat{B}_z/\widehat{B}_z$ (averaged over periods from 240s to 7200s in the frequency domain) which should be less than 0.2. The boundary of 20% error was a compromise between the minimum number of good data necessary for determining the transfer function in time domain method, and their quality. This parameter is related to the relative prediction error $\delta\widehat{B}_z/p\widehat{B}_z$, and its small values indicate that the segments do not contain the external part of B_z.

In order to make sure that we are not dealing with local disturbances, we additionally checked whether the non-induction signal is of a regional nature (is similar in the neighboring observatories). After the selection, we compare the estimation results for these two data types to assess how the source effect can change the estimation results.

Similarly, to the procedure described above, we can determine the prediction errors of electrical components (δE_x, δE_y). The predicted errors can be obtained by subtracting from the recorded electric components their predictions calculated on the basis of impedances.

Interesting conclusions can be drawn from the analysis of the variability of prediction errors over time. In Figure 3 we present examples of such a calculation for two months in the form of a plot of the ratio $\delta\widehat{B}_z/\widehat{B}_z$,

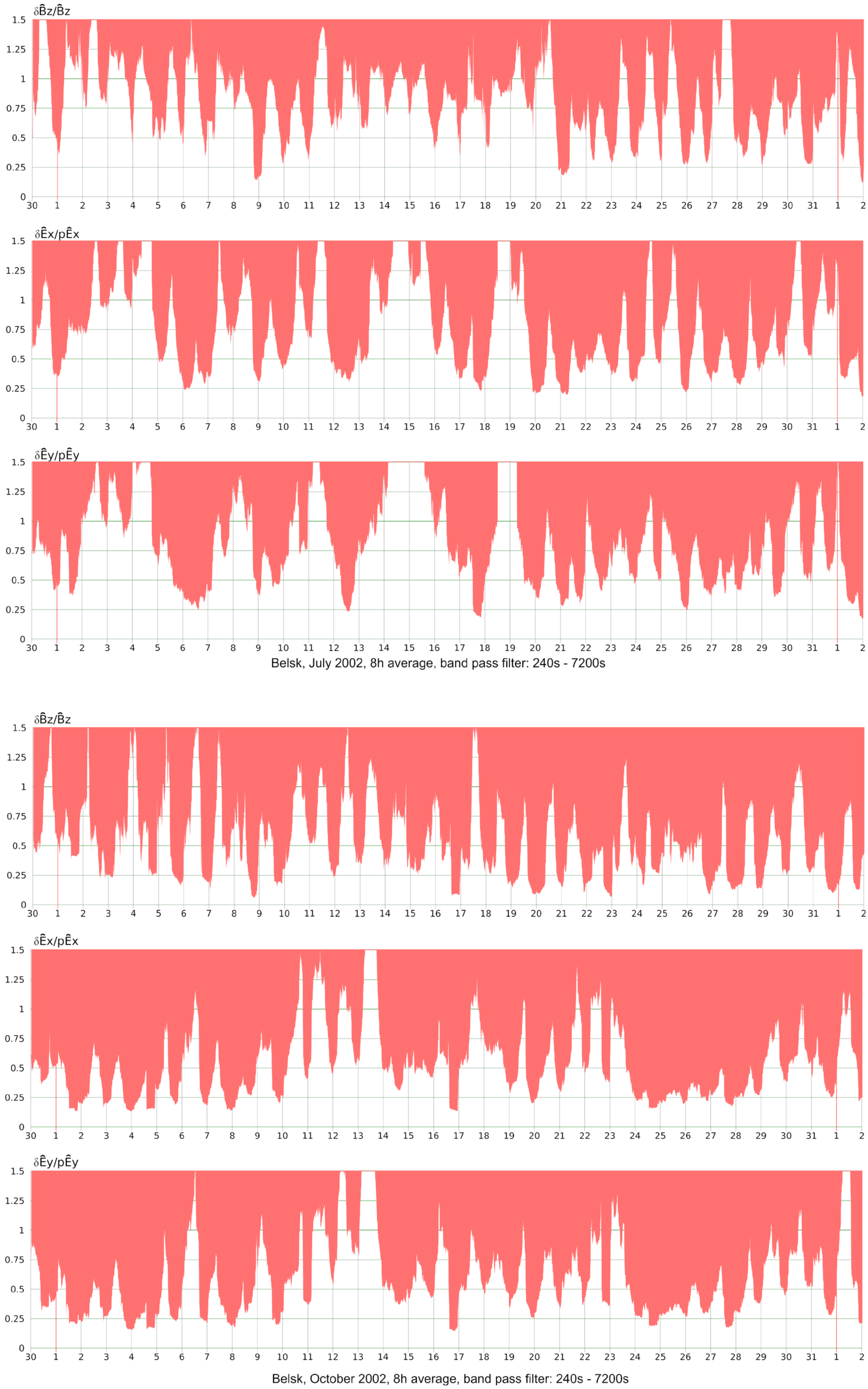

Figure 3. Plots of the ratio $\delta\widehat{B}_z/\widehat{B}_z$, $\delta\widehat{E}_x/p\widehat{E}_x$ and $\delta\widehat{E}_y/p\widehat{E}_y$ (moving averages over periods from 240s to 7200s in the frequency domain) as a function of time. Length of moving intervals is 8 hours each, with 1 min sampling rate. To enhance the readability of the diagram, values exceeding 1.5 (150% error) are truncated, and the areas in excess of the function value are shaded red.

$\delta\hat{E}_x/p\hat{E}_x$ and $\delta\hat{E}_y/p\hat{E}_y$ (moving averages over periods from 240s to 7200s in the frequency domain) as a function of time. Length of moving intervals is 8 hours each, with 1 min sampling rate.

An analysis of the distribution of prediction errors shows that the prediction errors of the vertical magnetic component and horizontal electric components are clearly greater during the day than during the night. This confirms the observation that during the day we encounter the presence of a vertical component in the external field more often. And this is why the daytime shift function differs from that of the night-time shift. The figures also show that the distributions of the $\delta\hat{B}_z$ and $\delta\hat{E}_x$, $\delta\hat{E}_y$ errors are similar. Similar to the prediction errors of the vertical magnetic component, the errors in predicting the electrical components in the case of day-time data and, consequently, from the summer period when the days are the longest, are larger.

It is worth noting, however, that although the prediction errors differ significantly, they do not have a significant impact on the result of the impedance estimation. Moreover, the estimation of impedance calculated from all data is similar to that obtained from the night-time data. This is because robust algorithms have built-in mechanisms for automatically attenuating the impact of "bad" data. And then the negative impact of the data portions that do not fulfill the plane wave assumption is significantly weakened. However, this algorithm property makes the assessment of the impact of the source effect on specific data segments difficult, and makes it difficult to control the quality of the processed data in the case of limited amounts of data. Therefore, in the next step, we use a time-domain algorithm to evaluate the impact of the source effect. Using the procedure described above, we have selected a few data sets in which we observe the presence of the vertical magnetic component in the external field (the plane wave assumption is not fulfilled for them). After selecting the data segments for which the prediction error is $\delta\hat{B}_z$ large, we checked whether it was caused by a deviation from the assumption of a plane wave or by local disturbances. For this purpose, we compared these non-induction components (time series) of pb_z at the Belsk observatory with the corresponding data from the Niemegk observatory. The similarity of these components proves that the effect of deviation of the incident wave from the assumption of a plane wave is regional.

The examples of such data for Belsk and Niemegk observatories [INTERMAGNET, 2013] are presented in Figures 4. The figures show 3-day time series, in which the two upper curves are the recordings of the horizontal components of the non-induction (external) part of magnetic field δb_z, and the lower two are the prediction errors of electric components δe_x and δe_y. The similarity of the top and bottom curves is noticeable. We also see how accurate the prediction is when the b_z, component does not contain the external part.

The transfer function estimation for data sets that do not fulfill the plane wave assumption are presented in Figure 5. For comparison, the figure shows also the results of estimation of fulfill the plane wave assumption data. It can be noticed that the results for the "bad" data clearly differ from the results for the "good" data and the difference may be 10-15%. This difference is a result of additional induction currents (eddy currents) appearing within the Earth due to changes in external vertical magnetic field (Faraday's law). It seems that for soundings done in another location this difference might be even bigger because it most likely depends on the geoelectric structure (geology) in the measurement site.

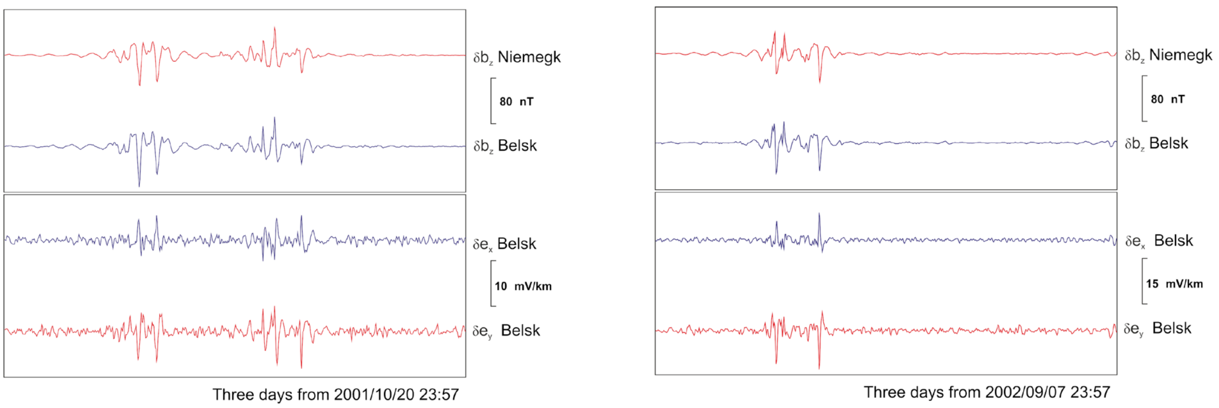

Figure 4. Samples of data with the external field deviating from plane waves in the form of 3-day time series; the top two curves are $\delta b_z(t)$ for the observatories in Niemegk and Belsk; the two lower curves are errors in the predictions of the telluric components δe_x and δe_y.

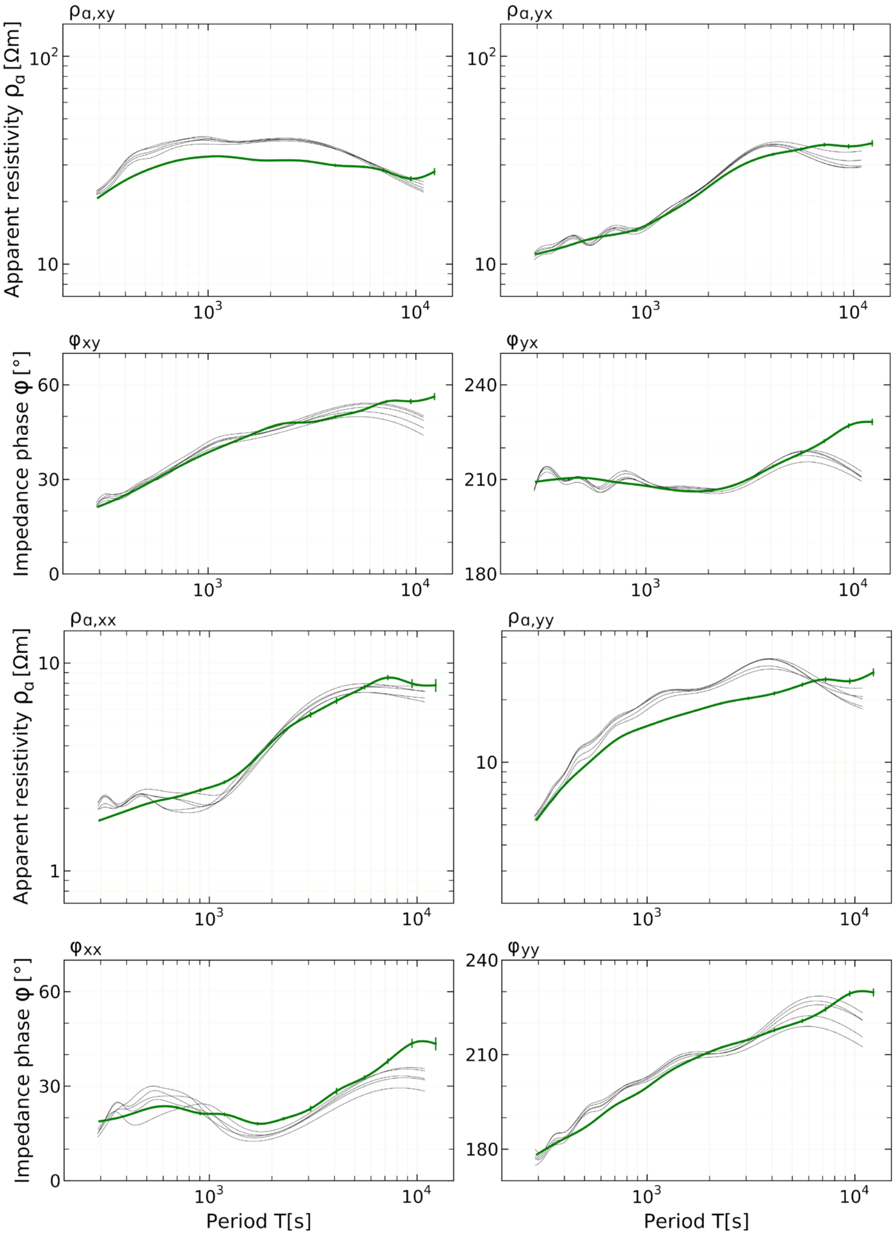

Figure 5. A comparison of the results of the transfer function estimation for data that fulfill (green color) and do not fulfill the plane wave assumptions (black).

Interestingly, the impedance curves for all "bad" data portions are similar. This proves that the presence of a vertical component in the external magnetic field of the source signal causes a similar upward shift of the apparent resistivity curve. This confirms the conclusion drawn from the comparison of the prediction error δb_z distribution that these "disturbing" current systems in the ionosphere, although occur sporadically, are always of a similar nature.

4. Conclusions

- The influence of the source effect on the result of impedance estimation is small, much smaller than it is in the case of VTF.
- No seasonality effect is observed. Impedance estimation for individual months gives almost identical results.
- The results of impedance estimation only from day-time data and only from night-time data differ slightly. This is the result of a statistically greater presence of a non-plane wave in source signals during the day.

- The variability of the electric components' prediction errors is very similar to the behavior of the prediction errors of the vertical component of the magnetic field, i.e. to the parameter describing the deviation from the plane wave. Usually, the minima and maxima occur simultaneously (similar trends can be observed).
- Occasionally, the source effect will affect the results of the impedance estimation. In the case of data that does not fulfill the plane wave assumption, the results may differ by several percent. The currently used robust algorithms can reduce this negative impact [Egbert and Booker, 1998]. However, when we have a small amount of data, it is recommended to carefully select the data and eliminate those for which the plane wave assumption is not fulfilled.

Acknowledgements. This work was partially supported by the National Science Centre Grant (NCN) number 2017/25/B/ST10/01348.

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