Subsurface Conductivity Obtained from DC Railway Signal Propagation with a Dipole Model

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Abstract

In the presented study, an attempt is made to model the propagation behavior of signals emitted by a Polish DC railway line with a number of grounded horizontal electric dipoles on the surface of a homogeneous half-space. The signals were measured on a magnetotelluric profile perpendicular to the railway line mainly in its near-field and transition zone, and they were separated from the natural electromagnetic variations by means of a reference site. Fitting the DC signals to the dipole model yields the conductivity of the homogeneous half-space. Its value for the vertical and for the perpendicular horizontal magnetic component is confirmed by the usual 2D MT model obtained from the profile.

Introduction

The electrified part of the Polish railway network (fig. 1) is run by DC current. This makes magnetotelluric (MT) studies in this country difficult. On the other hand, the “disturbing” (in terms of MT) signals emitted by this system propagate according to a dipole model (Oettinger et al. 2001 and citations therein) which contains, like MT, the electrical conductivity of the subsurface as a parameter. So, after designing and performing a MT field experiment comprehending railway signals in an appropriate way, it should be possible to obtain information about the subsurface conductivity by both the dipole model and the MT approach. By this idea the present study has been motivated.

The methodology of this study lies somewhere in-between two other domains encountered in geophysics. One is certainly the electromagnetic methods of the controlled-source near-field branch. The difference to our case is that the source is more under control there, but in return not free of experimental effort. The second related domain is techniques for modeling the propagation behavior of disturbances from DC railways and cables, applied especially to investigate their influence on magnetic measurements run at observatories (e.g. Pirjola et al. 2007, Lowes 2009, Maule et al. 2009). However, the induction character of this propagation including phenomena like frequency-dependent damping, phase shift, and the electric conductivity as a propagation parameter is almost completely omitted there in contrast to the approach presented here.

In the following, there will be considered the data processing including the separation of the natural electromagnetic variations from the railway signals and the estimation of the transfer functions between different stations. The dipole model will be described and the data be inverted according to it. The conductivity result will be compared to the output of a usual 2D MT model.

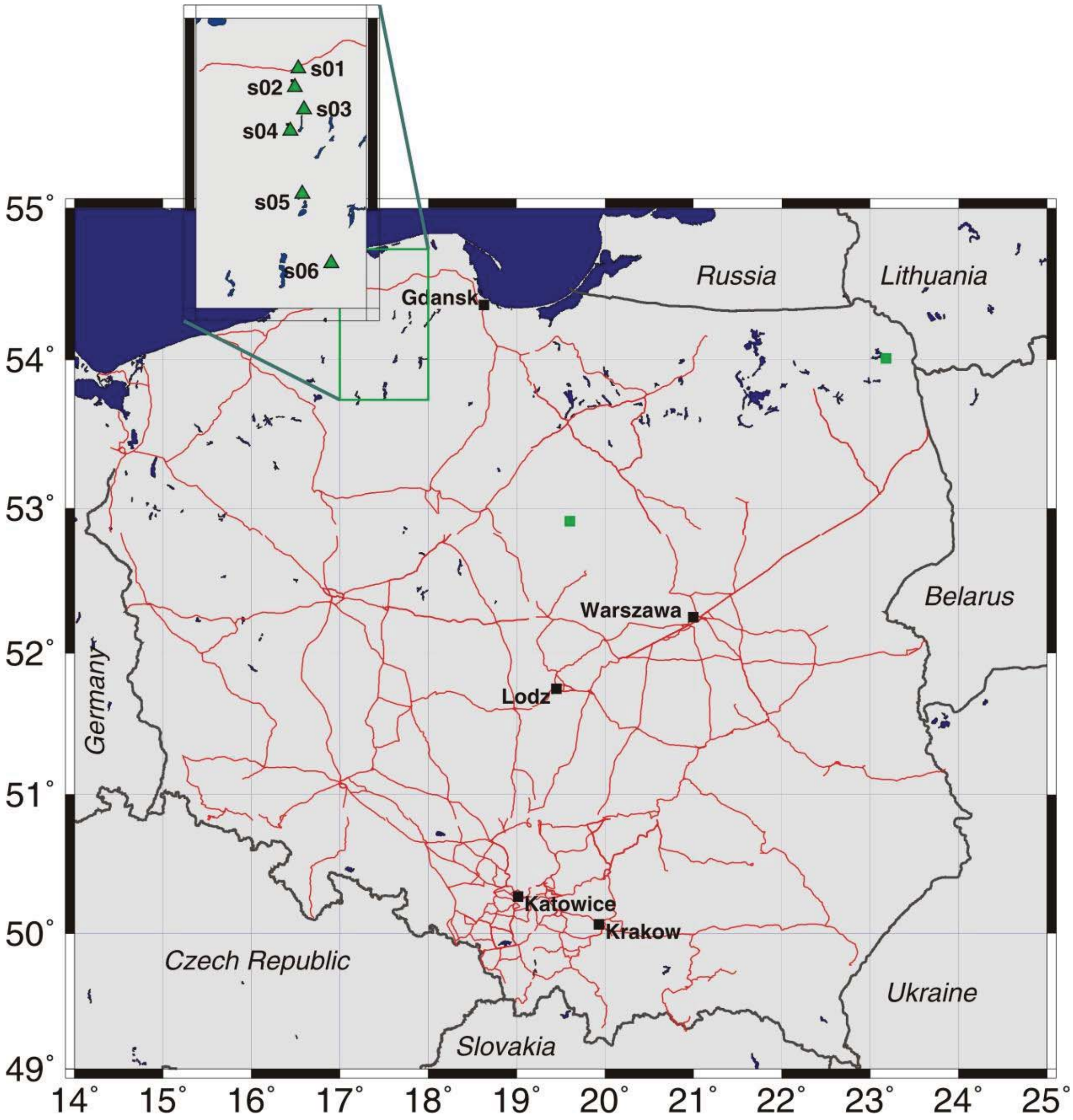


Fig. 1 The electrified part of the Polish railway network (red lines) with a profile of MT sites for investigation of one line (zoomed-in part). Green squares denote positions of reference stations.

Measurement and data processing

As shown in fig. 1, a profile of six MT sites has been installed perpendicular to an isolated railway line. The distances of sites to the line were 0.8, 7, 16, 25, 50, and 75 km. Two remote reference sites were set up at relatively noise-free places, and the whole array was running synchronously. The obtained data were processed with codes by Neska 2006, but not only for MT purposes. By means of its correlation to the reference sites, the natural part of the electromagnetic signal could be removed from the measured data using a method by Larsen et al. 1996 (fig. 2). In this way a dataset for analysis of the railway signals was established (cf. fig. 3). It has to be emphasized that it can be problematic to work with such “deduced” data, since distortions introduced to it during the separation, e.g. due to uncorrelated noise in the reference site, can bias the subsequent results. It proved useful to separate the data of the station closest to the railway which plays a special role in the following with one reference site and the rest with the second one.

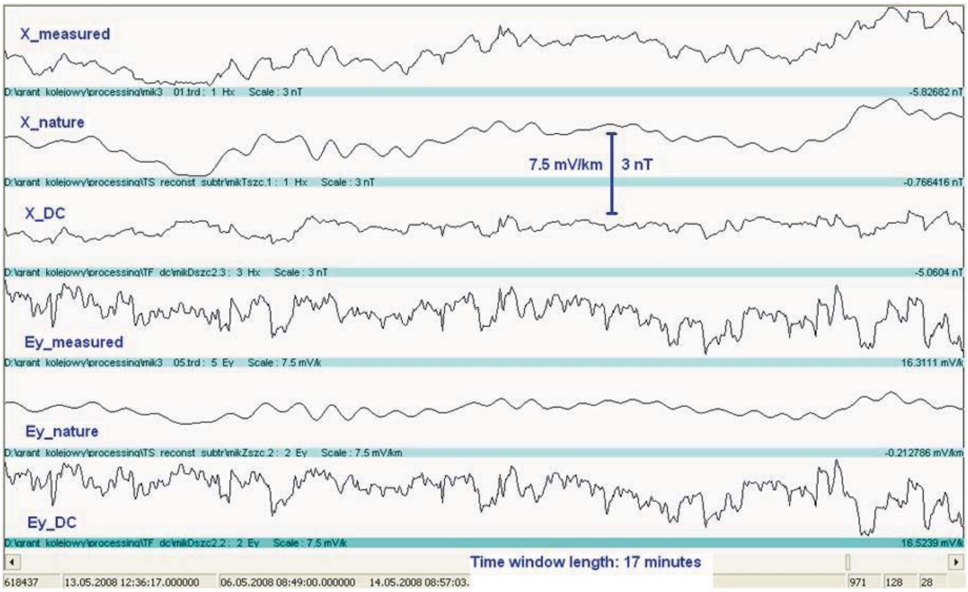


Fig. 2 Separation of time series into a “natural” and a “railway” part (site s02, see fig. 1).

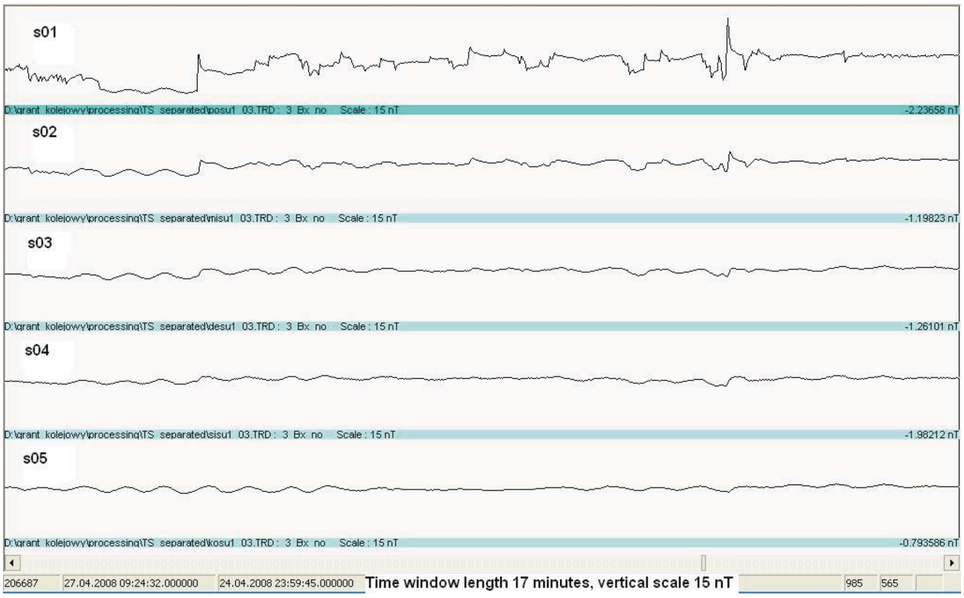


Fig. 3 The propagation/decay of railway signals (component Bx) over the profile. Note that a rest of natural variations remained in the time series in spite of separation.

All following considerations refer to “railway data” separated from natural signals in the way indicated above.

The formulas for the dipole response are given in frequency domain, so our calculation has to take place there. Furthermore, in these formulas there occur factors like current I and dipole length L (see table 1), i.e. technical parameters of railway traction which we cannot measure immediately. So it appeared reasonable to remove these factors by normalizing each field component to that of the railway-nearest site which represents the strongest, most pronounced, or least attenuated railway signal, respectively.

To perform this normalization in a convenient way, the algorithm for calculation of the inter-station transfer function or Horizontal Magnetic Tensor (HMT) was used, which played an essential role during the separation already. The site nearest to the railway takes the function of the reference, i.e. its data are input channels, and the data of the remaining sites are the output channels. So Bx and By data of “local” and “reference” sites lead to normalized values for both horizontal magnetic components, Ex and Ey to those for the electric components (even if the analogy to the HMT is overstretched here since it refers to magnetic data only, the formalism is the same), and Bz and some other, uncorrelated channel (e.g. of one of the real, off-profile references, just to fit the requirement of the HMT formalism that there must be two input channels) to the normalized value for the vertical magnetic component. This description remains a bit vague because it cannot be recommended for imitation for the following reason:

For this study, it has been noticed too late that this approach is not quite correct. The problem is that the HMT formalism bases on bivariate statistics (i.e. there are two independent variables or input channels, respectively), whereas the railway provides only one independent source polarization (pers. comm. K. Nowożyński). A similar problem occurs in Controlled-Source MT, where only one scalar transfer function instead of the usual 2x2 impedance tensor can be obtained if only one transmitter is used (pers. comm. M. Becken). So it has to be expected that our normalized values are influenced in an unfavorable way. This impact is expected to be very small in the case of Bz, since the warranted uncorrelatedness of the second input channel should make the difference between the univariate and the bivariate result vanish. This will be confirmed in the following section (cf. fig. 4: better result for Bz). However, the direction of the railway line under investigation is almost East-West (fig. 1), so its signal has a polarization almost coinciding with one of the directions we measure and calculate in with the MT or HMT approach. So there is hope that the error introduced due to this wrong statistic approach is somehow bearable if the diagonal elements of the “HMT” are used.

Finally, the normalized values are displayed over period and distance in 3D-plots (red lines in fig. 4). The decay of amplitudes with distance as well as their period-dependency (stronger damping at low periods) becomes clearly visible for Bx and Bz components. Bx has partly unsystematic and, especially at long periods, rather high values that make the impression to be distortions, maybe due to incomplete separation or the wrong statistic approach mentioned.

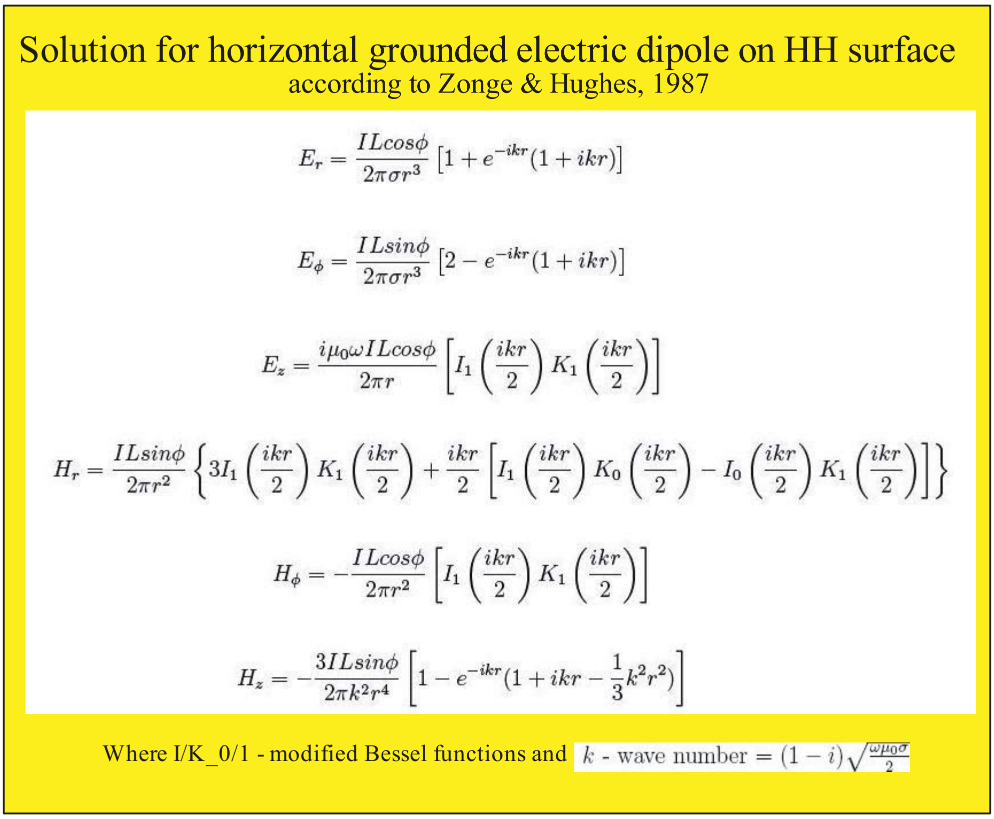
Hence the possibility to include data errors to the business was provided, since they have an important meaning as weights during the inversion.

The dipole model and its application

The railway line was simulated by a chain of horizontal grounded electric dipoles following its (not constant) bearing within a distance of some dozens of km around the profile. The distance between single dipole centers was 250 m. The solutions for the electromagnetic field components for the quasi-static approximation are taken from Zonge & Hughes 1987 and hold for one dipole on the surface of a homogeneous half-space (see table 1). These values are transformed from cylindrical to Cartesian coordinates to match the measuring system of MT and summarized over all dipoles subsequently. Then the values for each component and station were divided by the value of the corresponding component of the station closest to the railway. Since we look only for one model parameter (i.e. the conductivity σ), the inversion consists just of testing the whole model space and selecting the value with minimum RMS. The relevant software related to the dipole model was created by K. Nowożyński.

The components behaving best in our study were Bx and Bz. The inversion of Bx alone gave a resistivity of 5 Ωm, that of Bz alone 14 Ωm, and the joint inversion 10 Ωm. The model response for the latter is shown in fig. 4 as blue lines.

Table 1



Solution for horizontal grounded electric dipole on HH surface
according to Zonge & Hughes, 1987

$$E_r = \frac{ILcos\phi}{2\pi\sigma r^3}\left[1 + e^{-ikr}(1 + ikr)\right]$$

$$E_\phi = \frac{ILsin\phi}{2\pi\sigma r^3}\left[2 - e^{-ikr}(1 + ikr)\right]$$

$$E_z = \frac{i\mu_0\omega ILcos\phi}{2\pi r}\left[I_1\left(\frac{ikr}{2}\right)K_1\left(\frac{ikr}{2}\right)\right]$$

$$H_r = \frac{ILsin\phi}{2\pi r^2}\left\{3I_1\left(\frac{ikr}{2}\right)K_1\left(\frac{ikr}{2}\right) + \frac{ikr}{2}\left[I_1\left(\frac{ikr}{2}\right)K_0\left(\frac{ikr}{2}\right) - I_0\left(\frac{ikr}{2}\right)K_1\left(\frac{ikr}{2}\right)\right]\right\}$$

$$H_\phi = -\frac{ILcos\phi}{2\pi r^2}\left[I_1\left(\frac{ikr}{2}\right)K_1\left(\frac{ikr}{2}\right)\right]$$

$$H_z = -\frac{3ILsin\phi}{2\pi k^2 r^4}\left[1 - e^{-ikr}(1 + ikr - \frac{1}{3}k^2 r^2)\right]$$

Where I/K_0/1 - modified Bessel functions and k - wave number $= (1 - i)\sqrt{\frac{\omega\mu_0\sigma}{2}}$

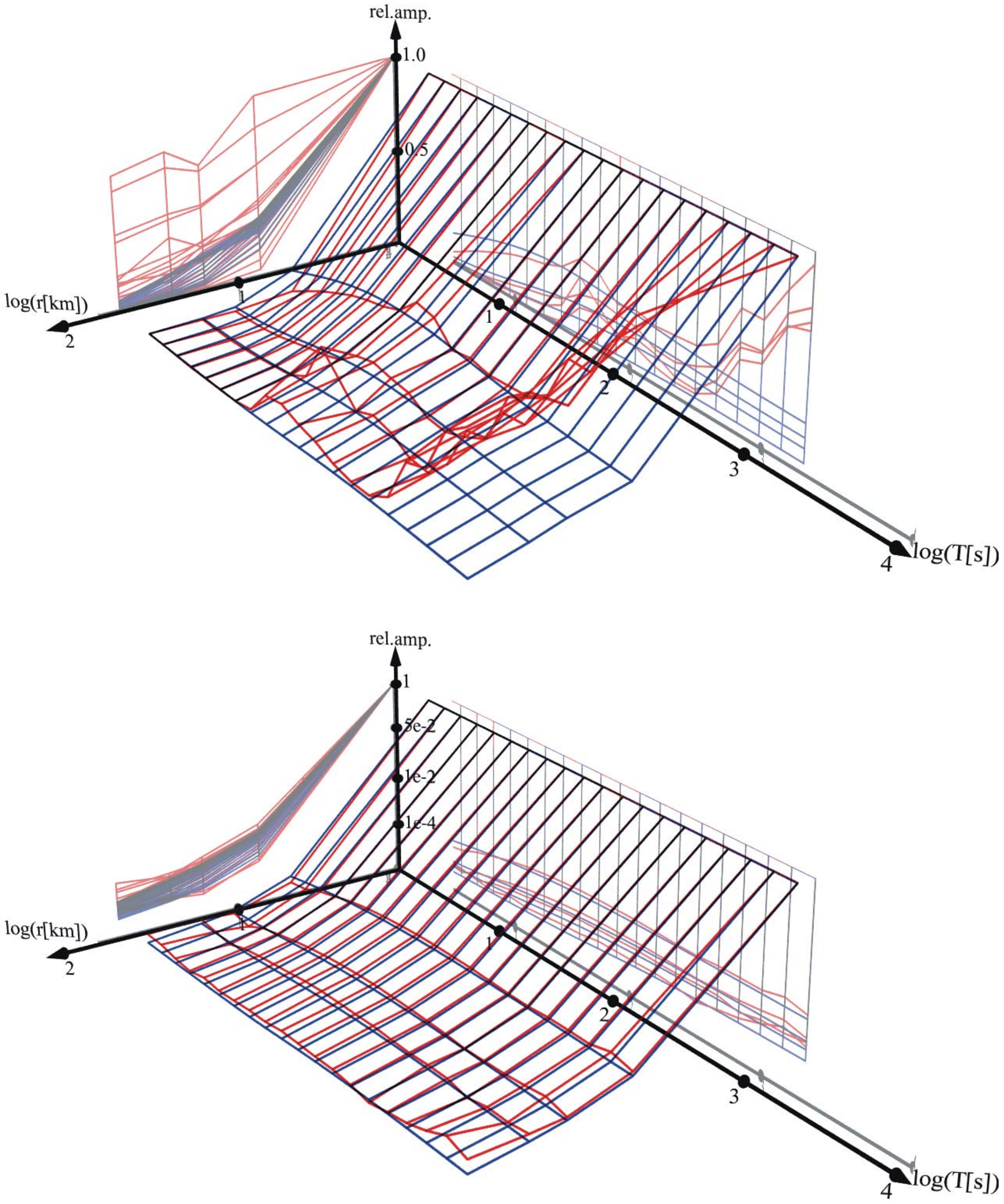


Fig. 4 Railway signal data (red) and dipole model response for a 10 Ωm homogeneous half-space (blue) over period and distance. Upper part for Bx, lower part for Bz component amplitude. The values on the vertical axis are normalized to that of site s01 nearest to the railway line (cf. fig. 1).

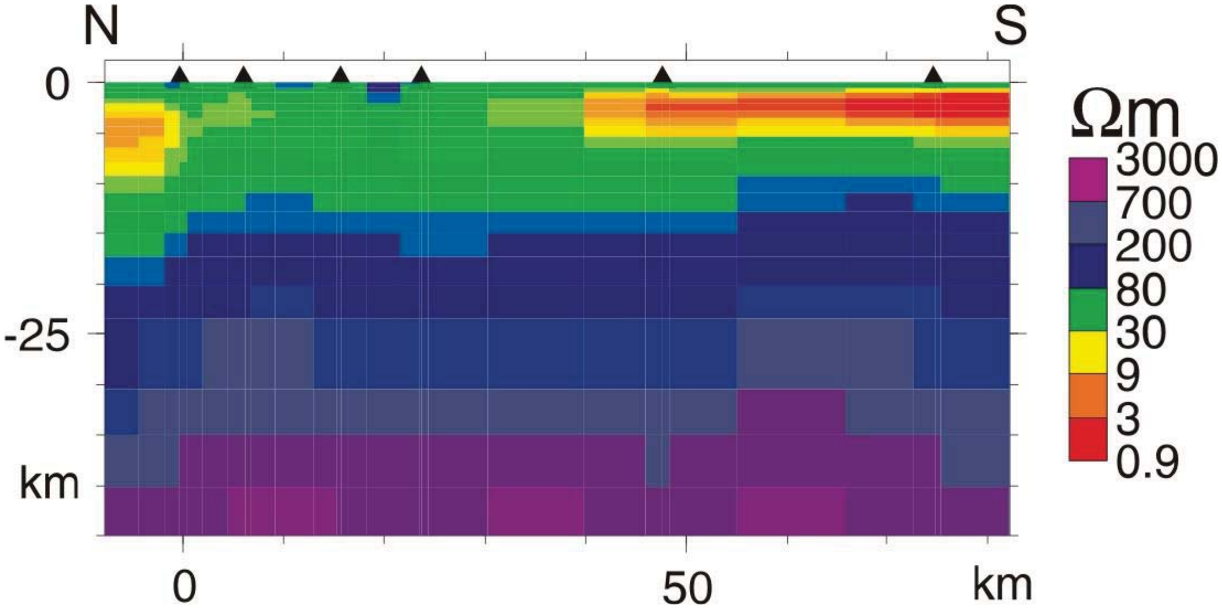


Fig. 5 2D MT model (TE and TM mode) of the profile on fig. 1 obtained with the REBOCC code (Siripunvaraporn & Egbert 2000). The shallow cells beneath the northernmost sites have resistivity values between 9 and 80 Ωm.

Discussion and conclusions

The MT model yields resistivities of 9-80 Ωm beneath the northernmost sites close to the railway (fig. 5). This is consistent with the dipole model result, so there is evidence that the dipole approach is not unreasonable.

Nevertheless, there are unexplained features in this model and one has to be critical with it. Not shown here is the behavior of phases and of electric components, where a similarity between data and model response is much harder to find for reasons still unclear.

However, taking into account first, the similarity of data and model response (fig. 4), and second, the compatibility of MT and dipole modeling results in spite of some quite principal problems in this implementation (i.e. input data biased during separation, errors due to application of bivariate instead of univariate statistics, limitation to the oversimplified case of a homogeneous half-space), there can be stated that the dipole model is not only a valid approach to model the propagation of DC railway signals, but even a relatively robust one.

Acknowledgements

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