Plane wave correction and 3D inversion of tensor CSRMT data

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SUMMARY

The plane wave correction of tensor CSRMT data measured in the transition zone of controlled source for the subsequent 3D inversion is proposed. Using 1D controlled source inversion of transition zone CSRMT data the plane wave curves were derived for main components of the impedance tensor. Efficiency of proposed correction was confirmed by the comparison with AMT curves. Corresponding CSRMT plane wave responses: apparent resistivity and phase curves were combined with AMT data and inverted using the ModEM three-dimensional code including topography. The obtained model was validated by the a priori geological information.

Keywords: Plane wave correction, Transition zone, Controlled-source radiomagnetotellurics, Audiomagnetotellurics, 3D inversion

INTRODUCTION

3D inversion of radiomagnetotelluric (RMT) data and controlled source radiomagnetotelluric (CSRMT) data in the far-field zone is based on the solution of the plane wave forward problem and is usually performed using magnetotelluric codes (Newman et al, 2003, Bastani et al, 2012). Modern computers and developed inversion codes like ModEM (Kelbert et al, 2014) permit to fulfill the inversion quite fast. Controlled source 3D inversion considering data in the transition zone of a source is the much more time-consuming task. There are still no publications about 3D transition zone inversion of the CSRMT data. Usually CSRMT measurements are performed both in the far-field and transition zones. Here we propose a relatively simple and fast procedure for the transformation of the mixed transition and far-field zone curves into fully plane wave equivalent curves without losing the phase and applicable for tensor CSRMT datasets (main components of impedance tensor). Validation of the proposed procedure was performed using the joint inversion of transformed CSRMT and audiomagnetotellurics (AMT) data and the comparison with a priori geological information.

Dataset

Field measurements were performed on the geophysics test site near St. Petersburg, Russia. For CSRMT measurements we used the RMT-F 5-channel recorder and two GTS-1 transmitters (Saraev et al, 2017) with perpendicular grounded wires of 620-630 m length. Measurements by the CSRMT were fulfilled in the broadside area of perpendicular wires at offsets from 13 to 640 m along 9 profiles with 50 m step and 20 m separation between stations along a profile. At the realization of soundings three main frequencies were used: 0.5, 5 and 50 kHz with 9 odd subharmonics for each main frequency to cover the range 0.5-950 kHz with 27 points on the sounding curve. Tensor CSRMT measurements were performed using traditional consecutive switching on transmitters: one measurement when the first transmitter is switched on and second one when the second transmitter is switched on.

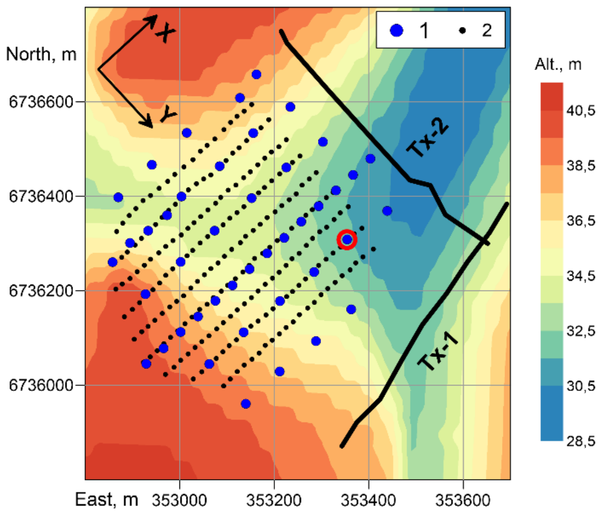

Figure 1. The layout of the sources and measuring stations in the topography map. 1 – AMT stations, 2 – CSRMT stations. Local coordinate system is shown in the map. Red circle shows the selected station for the analysis of transition zone effect.

Tensor AMT measurements were carried out using the 4-channel ACF-4M recorder (Saraev et al, 2014) in the frequency range 3-400 Hz. AMT stations were located on the regular mesh 100x100 m within the studied area. The layout of the measurement stations in the topography map is presented in Figure 1.

The range of topography changing is about 10 m in this area. Inversion was done accounting the topography. Local X-axis is directed along the profiles and local Y-axis – is across profiles.

An example of the CSRMT and AMT sounding curves is presented in Figure 2. A station was selected near the sources (red circle in Figure 1) to illustrate the impact of the transition zone effect on CSRMT data. We can see the significant gap between AMT and CSRMT curves because of transition zone effect.

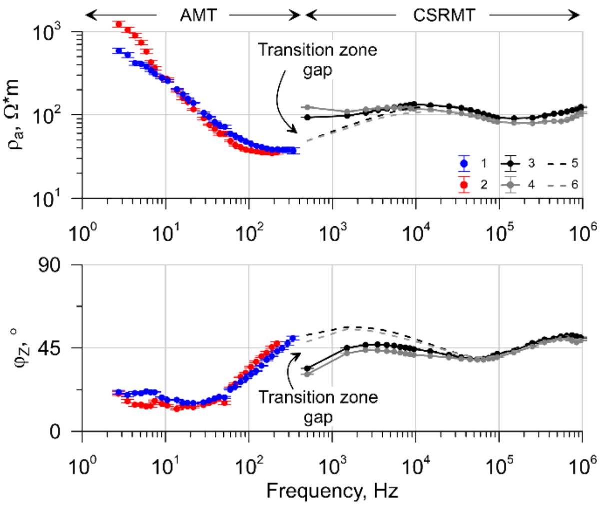

Figure 2. An example of sounding curves. 1 – XY AMT curve, 2 – YX AMT curve, 3 – XY CSRMT curve, 4 – YX CSRMT curve, 5 – synthetic plane wave curve after 1D inversion of XY CSRMT data, 6 – the same for YX CSRMT data. Position of the station is marked by a red circle in Figure 1.

Plane wave correction procedure

The correction procedure for transforming of the transition zone CSRMT data into the fully plane wave equivalent curves is described below.

Following to the principle of equivalence, we can say that any 1D model can be considered as an equivalent to the 3D model or the real distribution of the resistivity in the subsurface media if the electromagnetic (EM) response from this 1D model is close enough to the 3D response or measured data. It is valid for the plane wave and controlled source response (both, in transition and far-field zones). Almost any transition zone CSRMT data can be fitted with some acceptable tolerance using 1D controlled source inversion. For the obtained 1D model a plane wave response can be computed. We can assume that the computed 1D plane wave response is equivalent to the plane wave response from the real resistivity distribution on the measurement station.

In this context the task of 1D inversion of the transition zone CSRMT data is the fitting of measured data as close as possible but not the finding of a geologically reasonable model. The layered Marquardt inversion can be a good candidate for this procedure. For tensor data such correction has an obvious limitation. It is no way to correct diagonal XX and YY components but the main XY and YX components only. But the advantages of this approach are the independent fitting of each curve (XY and YX) and the joint correction of apparent resistivity and phase contrary to existing transition zone correction procedures like (Bartel, Jacobson, 1987).

Figure 2 contains an example of results of the application of proposed procedure. Dotted lines on the CSRMT curves are the corrected ones. It is clearly visible that both apparent resistivity ρ_a and impedance phase φ_Z AMT curves are naturally continued by the corrected plane wave CSRMT curves and we have smooth common curves over six decades of the frequency. For tensor CSRMT data in the transition zone when the diagonal components of the impedance tensor are small enough this procedure can be a reasonable alternative to controlled source 3D inversion.

Results of 3D plane wave inversion

For the 3D inversion we used the ModEM code (Kelbert et al, 2014). The full AMT impedance tensor data at 43 stations and the main components of the transformed CSRMT impedance tensor data at 222 stations were used at the inversion. The finite difference rectangular model had 65x58x62 cells with the inner horizontal part 700x540 m with size of cells 20x20 m. The first (top) 12 m part of the model was divided into 8 equal layers with 1.5 m thickness to discretize the topography. Each other layer of the model had the thickness 1.2 times bigger than a previous layer down to 68 km. Total size of the model was 53x53x68 km.

Inversion was performed using the nonlinear conjugate gradients (NLCG) algorithm (Rodi, Mackie, 2001). We used 2% error-floor for the main components of the impedance tensor and 15% error-floor for the diagonal components of the AMT data. Start resistivity of the model under the “air” cells was 40 Ωm. All AMT data and a priory geological information show that the basement of the section is presented by the resistive crystalline rocks. Using the smooth Occam inversion, the position of such sharp (by resistivity) border will be blurred and cannot be mapped confidently. In areas where the distance between AMT and CSRMT stations was less than 5 m we applied the 1D Marquardt joint inversion with 5 layers in the model using TM curves. For this inversion the original (not corrected) CSRMT data were used. As results of the 1D inversion the depths to the roof of the resistive basement were obtained in the range 220-310 m with slightly dipping toward the east with near to homogeneous the overlaying layer with resistivity around 30-60 Ωm and thickness around 140-180 m. According to a priory geological information this layer corresponds to the Riphaean sandstones and siltstones. Most of inhomogeneous are located in the top part of the section represented by Quaternary sediments. We estimated the topography of the top border of crystalline rocks and inserted this information to the start 3D model with the resistivity of basement 10000 Ωm.

For the 3D inversion the start RMS was 15.3% and final one after 60 iterations – 2 %. An example of fitting of the measured curves is presented in Figure 3. An example of section across the 3D model is shown in Figure 4 with overlapped a priori borehole information. The top part of section is the resistive Quaternary sands and loams. Its thickness matches the borehole data quite well. Lower we can see the more conductive layer with local resistive areas in the top, which corresponds to the Riphaean sandstones with gravel and pebbles. Lower part of model above the basement is the homogenies layer with resistivity of 30-40 Ωm which corresponds to Riphaean sandstones, siltstones and metasandstones. The resistive basement remained without any significant changes from the start model. This confirmed that our 1D estimation of the basement topography was correct. The top border of the basement according to geological information from one borehole in the vicinity of this area. It is presumed and shown by the dashed line in Figure 4. Our survey clarified the relief of this border. General view on the 3D model is presented in Figure 5.

CONCLUSIONS

The procedure for the plane wave correction of tensor CSRMT data in transition zone is proposed. Procedure is based on the 1D controlled source inversion of measured CSRMT data and the calculation of plane wave response for the derived model. The inversion is performed independently for XY and YX curves. As a result, we obtained the plane wave response, which is an equivalent to the AMT-RMT response which we can expect to obtain on the measuring station. Comparison with AMT data show that proposed procedure gets CSRMT response which naturally continue AMT curves. Using the 3D plane wave inversion of AMT and corrected CSRMT data we obtained the model which is in good agreement with a priori geology information.

ACKNOWLEDGEMENTS

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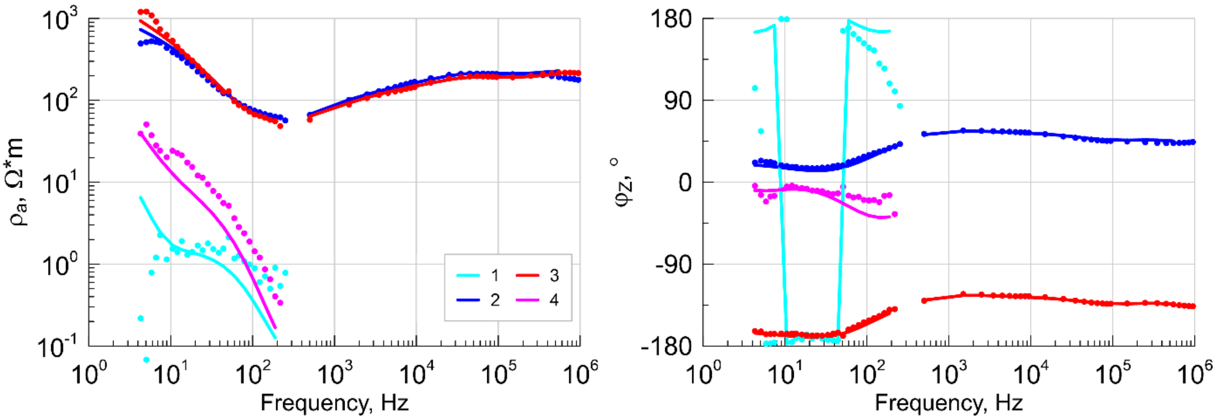

Figure 3. Comparison of synthetic and measured data for one station close to the sources. 1-4 – components of impedance tensor (1 - XX, 2 – XY, 3 – YX, 4 – YY), dots – measured data, lines – synthetic data.

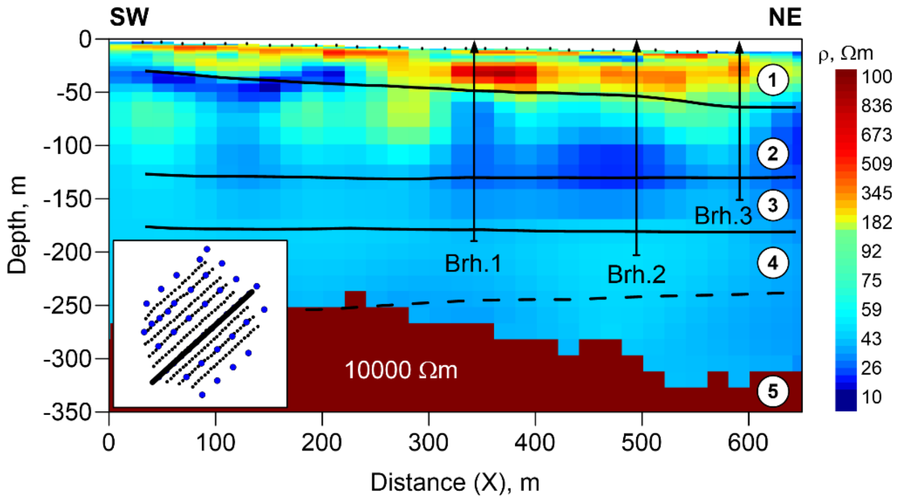

Figure 4. A section across the 3D model along the X-axis with overlapped borehole data. 1 – Quaternary sands and loams, 2 – Riphaean sandstones with gravel and pebbles, 3 – Riphaean sandstones and siltstones, 4 – Riphaean metasandstones, 5 – Precambrian crystalline basement (gneisses). The top border of the gneisses is not confident with borehole data but clarified by the resistivity section.

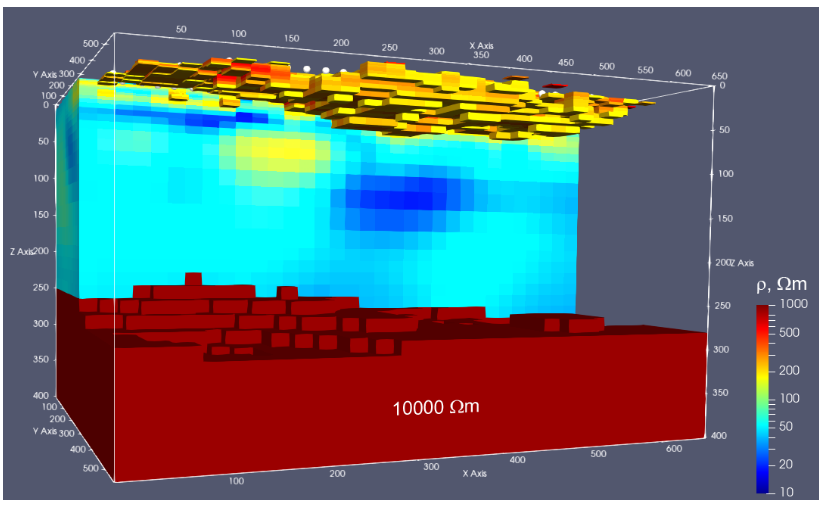

Figure 5. General view of the 3D model. Top resistive bodies correspond to the Quaternary sands. ~~and~~ Bottom resistive layer is the crystalline basement.