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PhD Thesis Summary

# ELECTROMAGNETIC IMAGING IN GEOPHYSICS WITH TENSORIAL INVARIANTS: FROM THE NEAR-SURFACE TO TRANSDANUBIAN DEEP STRUCTURES

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# INTRODUCTION

It is one of the most important challenges of natural sciences to improve our knowledge continuously about the Earth (which is our direct physical environment) and its physical and geological processes. It is a key problem to overcome for example from the present energy and environmental situation. There exist a variety of geophysical methods to analyse both the subsurface- and near-Earth space domains and to understand global and local environmental processes.

Electromagnetic geophysics is applied in various dimensions of earth and environmental sciences, e.g. in investigation of deep geological structures, mineral exploration, near-surface, environmental- and engineering geophysical, archaeological surveys. Electromagnetic methods also play an important role in understanding the Earth's magnetic field, various near-surface and deep geological phenomena.

Besides the traditional electromagnetic data processing, nowadays one can see more and more transformation solutions (especially for very large data systems), which provide images about deep geological structures and their dimensions free of the orientation of the measuring system. The key parameters of these transformations are called tensorial invariants.

In electromagnetic methods (including magnetotellurics) the mostly used interpretation method is the inversion. In order to obtain a physically correct solution (i.e. one of the realistic physical models of the subsurface) the model family should be selected. If the selected model family does not contain the true physical model, the solutions (although they are correct in mathematical sense) might be very far from the reality. Therefore the maximum potential of inversion methods can only be exploited by taking this kind of maximum risk in selection of the model family.

At the same time, the use of invariants does not need any premise or assumption about the subsurface, since the invariant images can be obtained through a simple transformation of the measured data. Practically there is no risk in use of invariant images, but we should see it clearly that they are able to provide a limited (but correct) information about the subsurface. The invariant quantities can be used in inversion processes as objective functions.

In magnetotellurics the invariant quantities – which provide full information about the magnetotelluric tensor – are used more and more frequently as interpretation parameters. The invariant systems can be used not only for imaging but also for dimensionality analysis. The various invariants of the impedance tensor (Swift, 1967; Berdichevsky and Dmitriev, 1976; Bahr, 1988; Bahr, 1991; Lilley, 1993, 1998a, 1998b; Szarka and Menvielle, 1997; Romo *et al.*, 1999; Szarka and Prácser, 1999; Martí, 2006), of the magnetotelluric tensor (Weaver *et al.*, 2000) and of the phase tensor (Caldwell et. al., 2004) provide very useful geological information. Experiments with invariants in DC mapping were discussed in bauxite exploration by Kakas (1981) and in analogue modelling Szarka (1984).

## 1. RESEARCH OBJECTIVES

The candidate intended to get a comprehensive knowledge about geologically meaningful features of invariant quantities and their relation to traditional interpretation parameters. Therefore the main objectives were as follows.

1. To get a comprehensive knowledge about the basic imaging features and complex interpretation potential of invariants of the magnetotelluric tensor by applying numerical modelling technique

2. Application of classical magnetotelluric inversion and dimensionality analysis to the large (2D and 3D) datasets in two research areas in West-Transdanubia

3. Reconstruction conditions of the magnetotelluric impedance tensor from its invariant systems

4. Comparison of various invariant results with results of classical interpretations

5. Studying the role of real and imaginary parts of the magnetotelluric impedance elements in electromagnetic imaging, and studying their sensitivity to model parameters, resistivity contrasts and noise

6. Investigation of possibilities of tensor invariant imaging in geoelectrics, based on the potential-gradient mapping method, including a field demonstration of constancy of invariant images when the electrode orientation varies

## 2. PERFORMED TASKS

The author took part in electromagnetic projects, investigating deep geological structures. He acquired and applied various magnetotelluric data acquisition-, numerical modelling- and data processing techniques. Besides various magnetotelluric variants and their classical data processing techniques he has become professional in robust processing technique, including two correction methods: the remote reference- an the statistical iterative robust algorithm.

He applied various numerical modelling and inversion algorithms (WinGLink, REBOCC, WSINV3DMT), and analysed the various results. He also applied one of the DC modelling codes (RES3DMOD, Loke, 2001) for studying imaging features of tensorial invariants.

The author also took part in developing of a DC geoelectric mapping method based on invariants: in the measuring and data processing and also in the field experiments. He carried out the measurements in an archaeological area.

### 2.1 THEORETICAL AND MODELLING WORK

The candidate paid a special attention to understand the relations among various magnetotelluric invariants, and to obtain a comprehensive knowledge about their imaging properties. He carried out theoretical studies to reveal the reconstruction possibilities of the complex impedance tensor from its independent invariants. The obtained relationships were applied also for the DC resistivity tensor.

The tensor invariant images were compared with the most generally used magnetotelluric and DC modelling- and inversion results, and various presentation forms were inter-compared, too (e.g. magnetotelluric polar diagrams, decomposition directions, etc.). He also carried out 3D numerical modelling experiments in order to reveal the model parameter-sensitivity, resistivity contrast-sensitivity and noise-sensitivity of invariants.

## 2.2 FIELD-RELATED WORK

As a participant of the OTKA (Hungarian National Research Fund) project No 40848, the candidate took part in the CELEBRATION-07 field magnetotelluric project (2003) as field geophysicist, then He took part in the data processing and interpretation. In 2006 the CEL-7 profile was continued in Austria, where he again fulfilled the same tasks. The data processing was fully my responsibility. With the help of students he digitized and re-processed the date base of 321 magnetotelluric stations in a related 3D magnetotelluric area. He carried out extensive experiments with the „Nagyatád" data base.

The author took part in the Pilisszentkereszt archaeological measuring project, where more than fifty thousand 2x2 resistivity tensors were determined. He carried out both the classical and invariant-based data processing, and he made a detailed comparison between them. The theoretical, field and methodological achievements were summarized in a separate chapter. He designed and realized a field experiment to analyse all possible effects of various current electrode orientations and positions on the resulting invariant responses.

Finally, He also took part in various DC parameter sensitivity modelling studies, where the depth of investigation and vertical resolution of all possible (about 30) DC arrays were determined on basis of thin-sheet responses.

# 3. ORIGINAL SCIENTIFIC RESULTS

Theoretical- and modelling results:

1. The author has collected and classified the invariant parameters related to the magnetotelluric impedance tensor. By means of numerical modelling (and by means of comparison with classical tools) he has demonstrated that the basic (1D) invariants provide a robust and realistic picture about the subsurface bodies. The shape-, side- and corner-dependent (1D, 2D and 3D, accordingly) features of invariants is summarized by using dimensionality analysis. As it has been found by noise studies, the most noise-sensitive invariants are the multidimensional (2D and 3D) ones, especially the 3D invariants. The polar diagram and phase tensor analysis tell that dimensionality parameters based on the phase tensor are more sensitive to lateral changes than other parameters.

2. He has demonstrated by extensive 2D and 3D numerical modelling that the real-tensor based invariants indicate deep structures at significantly shorter period than the imaginary-tensor based invariants or the mixed (traditional) invariants. The favourable imaging feature of the phase-based parameters (including the limited depth interval of the subsurface body) is due to the difference in the *Re*- and *Im*-based invariants.

3. He has analytically elaborated the conditions for the full reconstruction of the magnetotelluric impedance from its seven independent invariants and the given

orientation: maximum two invariants are allowed to be of second-order: one in the real tensor and one in the imaginary tensor, all other ones should be of first-order function of impedance elements.

Field results:

4. The main characteristic tectonic lines along the CEL-07 MT profile could be identified on basis of magnetotelluric results, both by using 2D inversion and invariant imaging. Among the Middle-Hungarian line, the Balaton line, the Balatonfő line and the Rába line it is the Balaton line, which manifests itself with the highest conductivity anomaly. The Middle-Hungarian line cannot be seen in the induction arrows. He has reminded to the unresolved origin of the electromagnetic anisotropy in the middle part of the CEL-07 profile.

5. The “Nagyatád” data base could be unambiguously interpreted due to the invariant images. The high-resistivity indications has nothing to do with the assumed high-conductivity Middle-Hungarian line. The long-period homogeneity of the phase invariant map refers to the depth-limited extension of the geological heterogeneity.

6. Using the database of appr. 50 thousand DC resistivity tensors obtained in the Pilisszentkereszt archaeological area (where the man-made resistivity changes could be separated from the natural ones) he demonstrated that the 2D and 3D invariants dispose with the theoretically expected (side- or corner-detecting) features, but they appear trustfully only in presence of significant anomaly, precise electrode-positioning and extremely low noise. While in the basic (1D) invariants are minimally affected by changing positions of he current electrodes, the 2D and 3D indicators change in a much more significant way.

General result:

7. The ensemble of theoretical, modelling and field results means a significant step toward recognising magnetotelluric invariant maps as standardized geophysical maps similarly to other geophysical (gravity, magnetic and telluric) maps.

## APPLICATION OF THE RESULTS

The magnetotelluric tensorial invariants are considered more and more as necessary tools for an exact interpretation. Therefore the present results are important first of all from methodological point of view. Moreover, the obtained geological results make it evident that in the future the geological interpretation cannot ignore these new geophysical results.

A comprehensive knowledge about the basic imaging properties and noise sensitivity of magnetotelluric invariants makes it possible to select the best possible invariant for the actual problem.

In geoelectrics, the invariant-based mapping is a new technique, with wide potential applications among others in near-surface and archaeological studies.

Both the magnetotelluric and DC noise sensitivity studies suggest that the multidimensional (2D and 3D) invariant parameters are less reliable than the 1D ones. Therefore the interpretation should perhaps be based rather on simpler 1D invariants, than the more complicated multidimensional ones.

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