RESEARCH REPORT ON THE RESULTS OF OTKA PROJECT K-109441

In the framework of the project (2013–2018), series expansion based inversion methods were developed for improving the interpretation accuracy in various field of geophysical research. The gravity and magnetic methods were tested in 3D models, the seismic, geoelectric/electromagnetic methods (DC, MT, IP) were investigated in 2D or 3D geologic models. In case of seismic method we dealt also with the forward modeling problem investigating the stress dependence of the seismic P- and S-wave velocities. In this case series expansion based inversion was applied in splitting the stress dependent velocities for characteristic (spectral) components. The project was prolonged one year in which (with the permission of the President of the OTKA Collegium) we extended our investigations to series expansion based inversion of borehole geophysical data and some geostatistical methods which were developed for increasing the stability and accuracy of the inversion. The results were published in refereed scientific journals (mainly with impact factor) and presented in international conferences. The support of the OTKA (National Research Development and Innovation Office) is indicated in all published papers and conference presentations.

Results of the first year

In the first year, we studied gravitational, geomagnetic, DC, MT and seismic 2D, 3D forward modelling methods. In case of solving DC direct problem the "transit" between series expansion and finite difference based discretization was solved, so the DC finite difference method of Spitzer became applicable in a "series expansion surrounding". Approximate solutions (1.5D, 2.5D) were also investigated providing geophysical parameters to be studied in our inversion algorithms. As an important item of our series expansion based inversion development the 2D Fourier transform was developed on inversion basis. In order to find powerful inversion procedure, in the first research year we studied linearized and global inversion procedures. The development of computational hardware background was also started in the first stage.

Results: new inversion method and software development (in MATLAB), conference presentations and proceedings, preparation/publication of papers.

There are two main directions of our research in this period: extending the series expansion based inversion concept to 2D Fourier transformation and investigating seismic forward modelling in the field of stress dependence of the seismic P- and S-wave velocities. In the first subject the inversion-based 2D Fourier transform method was developed in which the complex spectrum was expanded in terms of scaled Hermite functions. The favor that Hermite functions are eigenfunctions of Fourier transform was included in the algorithm resulting in high reduction of computation time. The application of Steiner weights was proved to be useful in this new Fourier transformation (IRLS-FT). The results are summarized in a paper published in the **Mathematical Geosciences** (47:(6) pp. 679-697). We applied the new robust IRLS-FT method to calculate the seismic attribute (reflection strength) and showed that (compared to the traditional methods) the signal to noise ratio can be sufficiently improved. This result was published in the **Magyar Geofizika** (55:(1) pp 21-29) and it can be applied in the interpretation of 2D/3D seismic data. We proved that the joint use of series expansion (by cell-wise constant basis functions) and the Steiner weights results in a robust seismic tomographic inversion (published in the **American J. Computational Mathematics** 4: (1) pp. 37-46.) As a further investigation of seismic forward modelling the development of stress dependent rock physical models for the velocity and quality factor of seismic/acoustic waves was also continued for P and S waves. In order to find powerful inversion procedure we studied linearized and global inversion procedures including genetic algorithm **Intelligent Control and Automation** (4: (4) pp. 362-370). Because of the much higher time consumption of global optimization we prefer linearized inversion during our research period. In this research year the results reached in series expansion based refraction seismic inversion were summarized in a PhD thesis leaded by senior participants of the OTKA project.

Results of the second year

In the second project year further development were taken in series expansion discretization based direct problem-solving procedures (exact and approximate) in case of DC, MT and the seismic forward modelling was investigated in stress-dependent physical models. The reduction to pole of magnetic data was studied and combined with the 2D series expansion based Fourier transformation procedure. This problem required extended software development in MATLAB. The software was tested and used for interpreting synthetic dataset. Further investigation of inversion procedures was carried out to test the stability and accuracy.

Results: new inversion methods of gravity and magnetic data and MATLAB software development, conference presentations and proceedings, construction and publication of papers.

The most important results of the research period were reached in the field of Series Expansion based Fourier Transformation: we made some generalization of the method and the paper discussing the robustification of our inversion based Fourier Transformation was published in the **Acta Geodaetica et Geophysica**,(49:(1) pp. 95-104.) in which we applied the Most Frequent Values method of Professor F. Steiner and involved his weights (calling them Steiner weights in the paper). We continued the program development of the IRLS-FT (in MATLAB) and tested it. Note, that the PhD Thesis of **H. Szegedi** (an employee of the OTKA project) discussing in details the inversion based FT method was presented and defended at the Department of Geophysics, Miskolc in March, 2015. The new results of the use of series expansion based inversion in the (3D) interpretation of gravity data were published in **Geoscience and Engineering** 4:(6) *pp. 81-92.* New results in the development of Series Expansion based magnetotelluric inversion method were reached, the paper presenting the results was published in **Magyar Geofizika** (56:(2) *pp. 97-107*.). Our main results in seismic method development are related with the pressure dependence of the propagation characteristics (phase velocity and Quality factor) of seismic/acoustic waves. We summarized our results in a detailed study on the pressure dependence of the Lame-coefficients in the **Acta Geodaetica et Geophysica**, 50 (3) pp. 339-352. A paper discussing the pressure dependence of the attenuation coefficient (seismic Q, the Quality factor) was published in the **Near Surface Geophysics** (12:(3) pp. 427-436.) The concept of Series Expansion based inversion has very important application in the field of borehole geophysics. Accepting the request from Springer, we summarized our related results in a book chapter (**Springer International Publishing**, *pp. 245-268*).

Results of the third year

Studying the noise sensitivity of the new inversion methods. Development of robust/resistant inversion procedures. Testing the developed algorithms on synthetic and in-field data. Extending the research to interpretation of borehole geophysical data.

Results: new inversion methods, software development, conference presentations and proceedings, publishing publications.

The most important results of the research period were reached in the field of Series Expansion based inversion extended to borehole geophysics. The results were published in the Q1 category journal **Geophysics** (81: (2) pp. D163-D175). Another (borehole geophysical) paper about the hydraulic conductivity in shallow groundwater formations was published in **Acta Geodaetica et Geophysica** (50:(4) pp. 461-477) and in **Magyar Geofizika** (56: (2) pp. 70-82), in which the method of Prof. Csókás was compared with the Kozeny–Carman model and our new procedure using factor analysis was included. (The development of these borehole geophysical methods are related to our main subject indirectly: the apriori knowledge of certain petrophysical parameter can reduce the number of the inversion unknowns, resulting in more stable inversion results.) We continued our research in rock physical model development, the new results were published in **Bányászati és Kohászati Lapok - Bányászat** (149:(1) pp. 16-21). and in **Geoscience and Engineering** (2:(4) pp.47-58). We continued the extension of series expansion based inversion method to MT method, the paper containing our result was published in **Magyar Geofizika** (56: (2) pp. 97-107). We extended the concept of series expansion based inversion to the field of geoelectric tomography (Gyulai et al., **78th EAGE Conference and Exhibition, Vienna**). We presented our new results in acoustic hysteresis in (Dobróka and Somogyi-Molnár: **7th EAGE Saint Petersburg International Conference and Exhibition**).

Results of the fourth year

The most important results of the research period were published in Q1 category journals. New results in the DC geoelectric 3D application of the series expansion based inversion were published in **Surveys in Geophysics** (38: (2), pp 503–526. IF=3.761). Based on our experiences in robust (series expansion based) inversion we developed a new robust factor analysis method. Its application in the inversion/interpretation of borehole geophysical data sets was published in **Geophysics** (82: (2) D69-D83, IF=2.391). By using the method the accuracy and reliability of the series expansion based interval inversion can appreciably be increased. We consider as a very important result the publication of the Inversion Based Fourier Transformation in a book chapter published by **InTech Open Access Publisher** (pp. 3-23). New results in the interpretation of Induced Polarization data were reached and published in **Magyar Geofizika** (57: (3), pp. 98-105) and some more details in **Geosciences and Engineering** (5: (8), pp. 111-123). We continued our research in rock physics by generalizing the previously developed petrophysical models. The new (double relaxation) models - as special cases of series expansion based inversion algorithm – were tested by using laboratory measured data. The paper containing the results is published in **Magyar Geofizika** (58: (2), pp. 57-65). The model was further developed from double relaxation to multiple relaxation model, which is in complete agreement with the concept of series expansion discretization. The inversion procedure published in the same paper is a complete series expansion based method. At this point our research related to the seismic forward problem with rock physical model developments fully connects to our main subject: the series expansion based inversion (in the field of seismics/acoustics). This part of the research was connected to the PhD research of **A. Kiss** (an employee of the OTKA project).

Results of the fifth year

A demonstration of the applicability of the concept of series expansion based inversion (combined with the robustification by Steiner weights) in Seismic Tomography was published in **Geosciences and Engineering** (5: (8), pp. 111-123). As the research activity was extended to borehole geophysics new results were achieved: a new and robust factor analysis method was developed and applied to determine some important petrophysical reservoir parameters. The knowledge of these parameters reduces the number of unknowns of the series expansion based inversion, increases the overdetermination rate and improves the estimation accuracy in the interpretation. The results were published in the **Mathematical Geosciences** (50: (3), pp. 317-335). The rock physical background of the forward modelling is very important in the geophysical methods. A new concept of the rock physical background of the IP phenomenon was developed in the last project year, which is based on an analogy between the pressure dependent rock-physical models and induced polarization mechanism. The basis and the first result of its application was published in the **Magyar Geofizika**, (58: (4) pp. 248-252) and also in **Geoscience and Engineering** (5:(8) pp. 111-123). A new field of the application of our inversion based Fourier transform method was presented in a conference lecture (Proceedings of 9th ICCM, Rome, 2018., pp. 903-907). It was shown that the pole reduction algorithm using IRLS-FT is applicable in surface measurements with non-equidistant (even random-walk) arrays.

Summary of the results

The measured data are always contaminated by noise (measurement errors). An important tool to reduce the influence of noise to the interpretation/inversion accuracy is to increase the overdetermination rate (number of data relative to the number of inversion unknowns). In the project – as a tool ensuring sufficient overdetermination - the series expansion based inversion methods were developed to process and interpret the data of various geophysical methods (gravity, magnetism, seismics, DC geoelectric, magnetotelluric, induced polarization and borehole geophysics). The new inversion methods together their accuracy and reliability were tested using covariance and correlation characteristic calculated in the model space. In most of the methods we used Iteratively Reweighted Least Squares algorithm applying Steiner weights (developed in the framework of the Most Frequent Value method). The results were published mainly in highly respected international journals with impact factor, some of them are Q1 rated. A total of 25 full papers in refereed journals and two peer-reviewed book chapters were published in the project period. 9 of the papers were published in international journals with impact factor (the sum of impact factors is 14.648). Two papers appeared in Geophysics, the most respected journal in our profession. Similarly two papers were published in Mathematical Geosciences, which is one of the most respected journals in theoretical geosciences. (Both Geophysics and Mathematical Geoscience are frequently rated as Q1 or evenD1 category journal. In the project we have 4 papers in Q1 category journals, 2 of them belong to D1 category.) The results of the project were also published in 15 presentations shown in the most respected international conferences (organized by EAGE and IEEE).

In field and research period of the OTKA project 4 PhD student of the Mikoviny Sámuel Doctorial School of Earth Sciences presented and defended their PhD thesis. The scientific leaders of the PhD students are senior participants of the OTKA project.

PhD student	Date	Scientific leader	Title of the PhD Thesis
Noémi Paripás	2013.12.17	Dr. Tamás Ormos	On the examination of near-surface geological structures through the inversion of seismic refraction data
Réka Kavanda	2016.12.06	Dr. Ákos Gyulai	Method developement in the series expansion-based inversion subject with locally 1d forward modeling
Hajnalka Szegedi	2017.02.20	Dr. Mihály Dobróka	Inversion method development for reducing noise sensitivity of fourier transform
Anett Kiss	2018.06.26	Dr. Mihály Dobróka	Rock physical investigations of acoustic relaxation processes

List of the most important publications

(Though the publications imported from MTMT are connected to the project in the NKFI EPR system, here we show them separately in order to show Impact Factors, when relevant.)

Publications in International peer-reviewed Journals (with IF)

1. Dobróka M., Somogyiné Molnár J., Szűcs P., Turai E. 2014. Pressure dependence of seismic Q – a microcrack-based petrophysical model. **Near Surface Geophysics**, 12:(3) pp. 427-436. (DOI: 10.3997/1873-0604.2013047) IF: 1.179
2. Szegedi H., Dobróka M. 2014. On the use of Steiner's weights in inversion-based Fourier transformation: robustification of a previously published algorithm. **Acta Geodaetica et Geophysica**, 49:(1) pp. 95-104. (DOI: 10.1007/s40328-014-0041-0) IF: 0.543
3. Dobróka M., Szegedi H., Somogyi Molnár J., Szűcs P. 2015. On the Reduced Noise Sensitivity of a New Fourier Transformation Algorithm. **Mathematical Geosciences** 47:(6) pp. 679-697. (DOI: 10.1007/s11004-014-9570-x) IF: 1.777, (D1), (Q1)
4. Somogyiné Molnár J., Kiss A., Dobróka M. 2015. Petrophysical models to describe the pressure dependence of acoustic wave propagation characteristics. **Acta Geodaetica et Geophysica**, 50 (3) pp. 339-352. (DOI: 10.1007/s40328-014-0074-4) IF: 0.528
5. Szabó N. P., Kormos K. and Dobróka M. 2015. Evaluation of hydraulic conductivity in shallow groundwater formations: a comparative study of the Csókás' and Kozeny–Carman model. **Acta Geodaetica et Geophysica**, 50: (4) pp. 461-477.) IF: 0.528
6. Dobróka M., Szabó N. P., Tóth J., Vass P. 2016 Interval inversion approach for an improved interpretation of well logs. **Geophysics**, 81: (2) pp. D163-D175. (2016) (DOI: 10.1190/geo2015-0422.1) IF: 2.391, (D1), (Q1)
7. Á. Gyulai, P. Szűcs, E. Turai, M. K. Baracza and J. Fejes. 2017. Geoelectric Characterization of Thermal Water Aquifers Using 2.5D Inversion of VES Measurements, **Surveys in Geophysics**, March 2017, Volume 38, Issue 2, pp 503–526. (DOI: 10.1007/s10712-016-9393-z) IF: 3.761, (Q1)
8. N P Szabó, M Dobróka. 2017. Robust estimation of reservoir shaliness by iteratively reweighted factor analysis, **Geophysics** 82: (2) D69-D83. (DOI: 10.1190/geo2016-0393.1) IF: 2.368
9. Szabó N. P., Dobróka M. 2018. Exploratory Factor Analysis of Wireline Logs Using a Float-Encoded Genetic Algorithm. **Mathematical Geosciences** 50:(3) pp. 317-335. (DOI: 10.1007/s11004-017-9714-x) IF: 1.573, (Q1)

Publications in Domestic and International peer-reviewed Journals (without IF)

1. Szabó Norbert Péter, Dobróka Mihály, Kavanda Réka 2013. Cluster analysis assisted float-encoded genetic algorithm for a more automated characterization of hydrocarbon reservoirs. **Intelligent Control and Automation** 4:(4) pp. 362-370.
2. Somogyi Molnár J., Dobróka M. and Bodoky T. 2013. Explanation of pressure dependence of acoustic velocity based on the change of pore volume. **Geoscience and Engineering** 2:(3) pp. 63-72.
3. Dobróka M., Szegedi H. 2014. On the Generalization of Seismic Tomography Algorithms. **American Journal of Computational Mathematics** 4: (1) pp. 37-46. (DOI: 10.4236/ajcm.2014.41004)
4. Szegedi H., Dobróka M. 2014. Hilbert-transzformált előállítása inverziós alapú robusztus Fourier-transzformációval . **Magyar Geofizika**, ISSN 0025-0120 , 55:(1) pp 21-29.
5. Szabó N. P., Dobróka M., Hursán L. 2015. Édesvíztárolók szivárgási paramétereinek meghatározása a Csókás-eljárás alkalmazásával**. Magyar Geofizika**, 56: (2) pp. 70-82.
6. Prácser E, Dobróka M. 2015. Magnetotellurikus adatok sorfejtéses inverziója. **Magyar Geofizika**, 56:(2) *pp. 97-107.*
7. Somogyiné Molnár J. and Kiss A. 2015. Modelling the pressure dependence of p wave velocity and porosity on sandstones. **Geoscience and Engineering** 2:(4) pp. 47-58.
8. Völgyesi L., Tóth Gy. and Dobróka M. 2015. Inversion Recostruction of 3D gravity potential function encluding vertical deflections. **Geoscience and Engineering** 4:(6) *pp. 81-92.*
9. Somogyiné Molnár J., Kiss A., Dobróka M. and Szűcs I. (2015) An automatic test system to measure acoustic velocity data to prove the applicability of the new rock physical model. **Geoscience and Engineering** 4:(6) *pp. 22-35.*
10. Kiss A. 2015. How overdetermination and start model influence the estimation accuracy of an acoustic rock physical model. **Geoscience and Engineering** 4: (7) pp. 59-74.
11. Kiss A, Turai E, Pethő G, Dobróka M. 2016. Gerjesztett polarizációs laboratóriumi mérések inverziós feldolgozása, **Magyar Geofizika**, 57: (3) pp. 98-105.
12. Kiss A., Somogyiné Molnár J. 2016 Rugalmassági paraméterek nyomásfüggésének vizsgálata kőszén mintákon. **Bányászati és Kohászati Lapok - Bányászat** 149:(1) pp. 16-21.
13. Dobróka M., Turai E. 2017. A Gerjesztett Polarizáció fenomenológiai értelmezése kőzetfizikai analógiák alapján. **Magyar Geofizika**, 58: (4) pp. 248-252.
14. Kiss A, Dobróka M. 2017. Kőzetfizikai modellek továbbfejlesztése a szeizmikus/akusztikus sebesség és a jósági tényező nyomásfüggésének leírására. **Magyar Geofizika**, 58: (2) pp. 57-65.
15. Kale U. and Dobróka M. 2017 An introduction to Robust Tomography Methods. **Geoscience and Engineering** 5:(8) pp. 98-110.
16. Kiss A., Dobróka M., Turai E. and, Somogyiné Molnár J. 2017. Laboratory induced polarization data processed with series expansion inversion. **Geoscience and Engineering** 5:(8) pp. 111-123.

Peer-reviewed book chapters

1. M Dobróka, H szegedi, P Vass. 2017. Inversion-Based Fourier Transform as a New Tool for Noise Rejection, In: Goran S Nikolic, Milorad D Cakic, Dragan J Cvetkovic (szerk.) Fourier Transforms - High-tech Application and Current Trends. Rijeka**: InTech Open Access Publisher**, 2017. pp. 3-23. (DOI: 10.5772/66338) (https://www.intechopen.com/books/fourier-transforms-high-tech-application-and-current-trends/inversion-based-fourier-transform-as-a-new-tool-for-noise-rejection)
2. Dobróka M. and Szabó N. P. 2015. Well Log Analysis by Global Optimization-based Interval Inversion Method. In: Cranganu Constantin; Luchian Henri; Breaban Mihaela (Ed) Artificial Intelligent Approaches in Petroleum Geosciences. **Springer International Publishing**, *pp. 245-268.* (ISBN:978-3-319-16530-1)