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Review of the PhD Thesis by Bartosz OWOC *Analysis of the uncertainty of traveltime tomography in various scales of seismic experiments*

At first, I would like to notice that the topic of this thesis, namely, treating uncertainty of geophysical data and models, is particularly important nowadays, when the amount of free-access multidisciplinary geophysical data has increased dramatically and researchers can use freely available tools for application of advanced methods of data analysis, including big data and various Artificial Intelligence (AI) techniques. These methods are particularly important for research that aims at integration of the data from different geophysical and geological datasets. All these methods require that uncertainly in the original data is evaluated quantitatively and treated properly to minimise the effect of propagation of uncertainty to final interpretation results. That is why the problem considered in this thesis (*Analysis of the uncertainty of traveltime tomography in various scales of seismic experiments*) is relevant not only for seismic studies, but for general geophysical research as well. The advantage of the approach implemented in the thesis is that the problem of uncertainly is considered in various scales seismic experiments, from near-surface scale experiments to regional seismic studies. The thesis concentrates on a single technique (first arrivals travel time tomography, FATT) that nowadays is one of the most popular methods of seismic data interpretation. Moreover, travel time tomography is a first step in more advanced techniques like full waveform inversion (FWI), that is why it is important that uncertainty of FATT results is evaluated in accurate way.

The thesis is of monography-type, and the results presented in the thesis are partly published in peer reviewed journals and conference proceedings. The personal contribution of the candidate to the published results is significant and clearly delineated in the thesis text. The thesis demonstrates that the candidate's skills in geophysics has been developed during his PhD career stage and that the candidate is able to plan and carry out an independent research. So, my general conclusion after examining the thesis is that Bartosz Owoc is qualified for a PhD degree and is ready to proceed to the post-doctoral stage of his research career. In the following I provide more detailed analysis of the thesis, aiming mainly to evaluate the candidate's personal contribution to the results and conclusions.

The major scientific result of the PhD study is the methodology of qualitative evaluation of uncertainty of FATT due to such important factors as uncertainty of the starting model and uncertainty of travel times picking precision. The methodology is developed in the framework of general mathematical formulation of geophysical inverse problems (Chapter 2.1). In Chapter 2.6 the candidate demonstrates that he is familiar with the existing approaches to uncertainty evaluation in FATT and understands well the difference between accuracy and uncertainty (Chapter 2.6.1). The different types of uncertainty estimation proposed previously by other authors are analysed in Chapter 2.6.2.

The uncertainly analysis methodology proposed by the candidate is his original contribution and it is presented in Chapter 2.7, in which dependence of FATT on starting model and picking precision is discussed. The candidate proposes his own model-fitting estimator that can be combined with picking uncertainty estimator into a single qualitative uncertainty estimate (eqs. 15-17).

The results of application of the proposed uncertainty evaluation in FATT to synthetic and real data are presented in Chapter 3. The results of methodology of application to data of near-surface experiment are published in one regular paper (Ovoc et al., 2019a) and in one conference proceedings (Owoc et al., 2019b), thus they have been already presented to wider scientific community. One interesting contribution by the author that might be of interest for geophysical professionals is described in Chapters 3.1.1 *Acquisition optimisation* and 3.1.2 *Pre-processing optimisation*. The uncertainty analysis results presented in 3.1.6.2 and illustrated by figures are clear to understand. An important result of the study is demonstration how the proposed uncertainty estimator can be used to verify results of seismic imaging in the area where ground-truth data (e.g. drilling information) are absent. In Chapter 3.1.7 the candidate demonstrates general knowledge of the geology of the study area. The Conclusions related to near-surface case study (Chapter 3.1.8) are clearly written and relevant for future similar projects.

The results of application of the proposed methodology to industrial case data are presented in Chapter 3.2. These results are published only partly in an extended abstract in conference proceedings (Owoc et al., 2018). However, the candidate treats the lack of regular publication by providing quite detailed description of the study in this chapter. The major parts of the study are conventional for typical case-study geophysical publication (e.g. geological background, description of the fieldwork and data processing, description of testing with synthetic data) and they are presented in Chapters 3.2.1, 3.2.2 and partly in 3.2.3, respectively. Chapter 3.2.3 is addressing namely the problem of uncertainty evaluation using the proposed methodology and the candidate illustrates its application by quantitative uncertainty maps in Figs 17-19. The results of the uncertainty analysis are discussed in Chapter 3.2.3.2 and conclusions are made in Chapter 3.2.4. In Conclusions, the candidate compares the results of uncertainty analysis with those in the previously considered near-surface case and gives the conclusion that dependence of FATT on the starting model and travel time picking precision is similar for both cases. The candidate also proposes to use hit-count normalisation, in order to take into account ray coverage and to highlight non-physical artefacts in the final FATT models. Generally, this case study is a good example demonstrating usefulness of the proposed methodology.

The results of the next case study (Chapter 3.3 *Regional scale*) have not been published yet, so this chapter is a quite detailed description of the study that contains all the necessary information for understanding the work done by the candidate and for evaluating his personal contribution. As a case study, the candidate selected the S02 profile of SUDETES2003 experiment. The personal contribution of the candidate indicated in the beginning of Chapter 3.3 is significant. It includes all the major steps of this case study, including data reprocessing aiming to obtain the more visible Pn phase, forward and inverse modelling of synthetic and real original and reprocessed data, application of the proposed methodology of uncertainty evaluation to synthetic and real data, detailed discussion of the results and making conclusions. The selected example is important as it demonstrates how the proposed methodology of FATT uncertainty analysis can be utilised for retrieving reliable information about seismic velocities in the crust and the depth to the Moho boundary in wide-angle reflection and refraction experiment. The author compares results of

application of his methodology to the models obtained by two different inversion approaches: layer stripping and joint inversion, in which all the data are inverted simultaneously. My opinion is that the term "joint inversion" is used misleadingly in this context, as usually it means joint inversion of different (even multidisciplinary) data sets. Thus, it would be better to use other term in future studies and in regular paper describing results of this study.
The synthetic velocity model is based on results of previous seismic studies and geological information and it is quite typical for DSS experiments of similar scale. Thus, it can be said that results of synthetic modelling are of general importance, although only one profile data was analysed. In addition to impact of uncertainty in picking and in starting model, the candidate addresses partly the effect of input data quality, namely lack of the data in DSS experiments. The other important factor influencing the data quality (signal-to-noise ratio) is not discussed. It seems that the noise factor was not taken into account in synthetic modelling in Chapter 3.3.5. At least, I could not find this discussion in the text.
The results of application of uncertainty analysis to synthetic data are presented as a set of qualitative and quantitative uncertainty maps in Figs 27-32 and described in detail in the text of Chapters 3.3.5.6 - 3.3.5.8. From the synthetic data inversion and uncertainty evaluation the candidate concludes that joint inversion works better than inversion using layers stripping and that the proposed uncertainty analysis works correctly. The conclusion is justified and supported by the synthetic modelling results.

Chapter 3.3.6 shows application of the proposed methodology to real data of the S02 profile. In addition, it focuses on the enhancement of Pn phase signal using the procedure applied also to the industrial scale data (Chapters 3.3.6.2 and 3.3.6.3). Reprocessing of the legacy data done by the candidate can be considered as one of the advantages of his work, as the quality of Pn picking has been improved significantly due to application of ARSIP technique. Thus, the candidate not only verified his uncertainty estimation methodology, but also obtained new information about the Moho boundary for this profile.
The conclusions from the application of the methodology to data from regional scale experiment are presented in Chapter 3.3.7. The candidate is quite critical when discussing the results of both synthetic and real data modelling. Such self-criticism is one of the most important principles of scientific ethics, thus it can be considered as one of the advantages of the thesis. The results of inversion and uncertainty evaluation are discussed in detail and compared for two real data sets: original data and reprocessed data. It is shown that application of the proposed methodology of uncertainty evaluation is a useful tool and it helps to avoid overinterpretation of models obtained by FATT.

Generally, the thesis clearly demonstrates advantages of the methodology of uncertainly evaluation of FATT proposed by the candidate. The thesis can be considered as satisfying the requirements of monography-type PhD thesis.

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