The analysis of topography and distortion effects in real data:
A Case Study on 3D inversion of MT data from the Northeast Carpathian Volcanic Arc

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SUMMARY

The interpretation of magnetotelluric data (MT) acquired in the areas with rugged topography and galvanic distortion can be challenging. While 3D MT inversion algorithms capable of tackling these issues exist, their widespread adoption is hindered by ongoing development and complexities in implementation such as an inverse problem solution on multi-resolution adaptive meshes. Particularly, one way to mitigate galvanic distortion during the inversion process can be to introduce additional constraints on the data and weights in the objective function. However, this approach requires determining appropriate values for weights given varying data confidence levels, site distribution, and data coverage in terms of available periods at each site.

This communication presents our methodology for evaluating the impact of topography and distortion on the interpretation of MT observations, on the example of a 3D MT survey collected as a part of the geothermal resource assessment project at the Northeast Carpathian Volcanic Arc in Northern Romania. The study area is located in the Baia Mare mining district, characterized by scattered near-surface conductive anomalies and diverse terrain with significant elevation changes exceeding 800m between sites and 1300m across the model.

We use two different software packages to test various approaches for the quantitative interpretation of real data: a finite-difference ModEM code widely used for 3D MT inversion Kelbert et al (2014) and a more recently developed DEVA3DMT Varılsüha (2020) which is a hybrid finite element method and it is capable of accommodating both topographical features and estimating distortion parameters together with the inversion for resistivity of the subsurface. We assess the performance with both uncorrected and distortion-corrected data and highlight issues arising from incorporating coarse topography grids, such as near-surface conductivity anomalies and biased results in forward modeling, respectively. We evaluate the impact of each of the two factors by incorporating topography and distortion correction in the inversion workflow. Through this analysis, we underscore the importance of considering both topography and galvanic distortion in MT data interpretation, offering insights into the effectiveness of different inversion approaches.

Keywords: Magnetotellurics, 3D, Topography, Galvanic Distortion, Carpathian Mountains

INTRODUCTION

Galvanic distortion of the electric field (Chave et al, 2012; Jones, 2012) and topographic effects (Jiracek, 1990) remain significant challenges in 3D Magnetotelluric (MT) data interpretation. Distortions caused by near-surface conductivity anomalies can alter measured electric fields, leading to inaccurate subsurface conductivity models (Larsen, 1973; Berdichevsky and Dmitriev, 1976; Groom and Bailey, 1989a; Caldwell et al, 2004). Unresolved surface topography in the model introduces further distortions, leading to inaccurate forward modeling and deteriorating the stability of inversion.

Mitigating galvanic distortion typically requires advanced processing techniques applied to the data and/or inversion for additional model parameters at the MT site locations. Methods such as tensor decomposition and distortion matrices have been developed (Groom and Bailey, 1989a; Caldwell et al, 2004; Neukirch et al, 2019, 2020), though they often rely on assumptions that may not apply universally. Alternatively, incorporating distortion parameters into MT data inversion adds complexity, requiring extra constraints and weights (Avdeeva et al, 2015; Moorkamp et al, 2020; Varılsüha, 2020).

Addressing topographic effects necessitates detailed terrain modeling to correct for surface distortions (Nam et al, 2007; Usui, 2015; Käufl et al, 2018; Soyer et al, 2019; Varılsüha, 2020). The combined challenge of galvanic distortion and topographic effects underscores the need for sophisticated 3D inversion algorithms.

This study evaluates the impact of topography and galvanic distortion on MT data from the Northeast Carpathian Volcanic Arc, using ModEM (Kelbert et al, 2014) and DEVA3DMT (Varılsüha, 2020) inversion software. By comparing results obtained using the two forward modeling solvers and different inversion methods that are implemented in the software packages, we highlight the strengths and limitations of these algorithms to accurately model subsurface conductivity in complex terrains.

METHODS

We utilize 3D MT data from the Baia Mare mining area in Northern Romania (study region of about 50X50 km), collected from 36 magnetotelluric sites, supplemented with 5 additional sites where only electric fields were measured (Neukirch et al. 2024 in review). In this study, we examine two subsets of data derived from the collected measurements: (1) broadband data ranging from 128 Hz to 8,192 seconds, encompassing 36 MT sites and 5 pseudo-MT sites where the magnetic field from a neighboring site was combined with the local electric fields to assess topographic effects, and (2) long-period data ranging from 8 Hz to 16,384 seconds at the 36 MT sites to evaluate distortion effects.

We inverted the first subset of the data using three different setups: 1) using a finite differences approach in a flat Earth model (ModEM), 2) using a finite differences approach and incorporating topography (ModEM), and 3) using a hybrid finite element method incorporating topography (DEVA3DMT). All data were corrected for galvanic distortion effects before the inversion using the method by Neukirch et al (2020) based on optimization of the similarity between geometric amplitude and phase tensor parameters.

The computational domain consisted of a nonuniform grid with lateral dimensions of cells about 1 km. In ModEM, the cell thickness was set to 50 m for the first 25 cells, followed by progressively thicker cells, increasing by a factor of 1.2. In DEVA3DMT models, we used an adaptive mesh with a smaller initial thickness, increasing by a smaller factor from the surface.

The second subset of the data was inverted with and without distortion correction using ModEM and a flat Earth model. The model retained the same cell width of 1 km, but the cell thickness started at 10 m, increasing by a factor of 1.15 from the surface.

RESULTS AND DISCUSSION

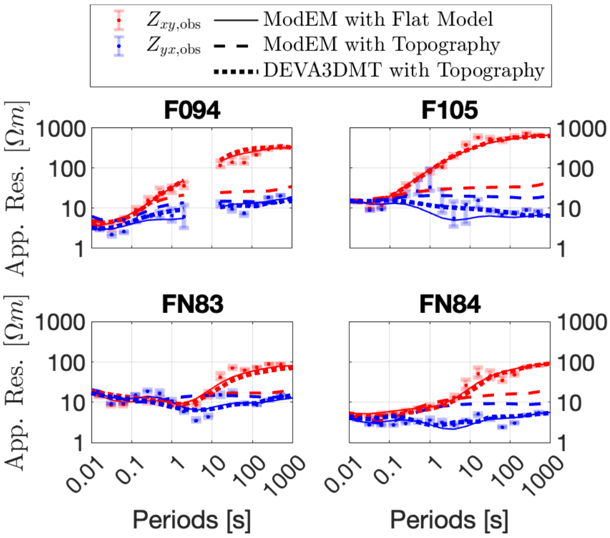

Figure 1: Apparent resistivity values for off-diagonal impedance tensor components and modelled impedance components presented for the three inversion setups. The observed data are presented for 4 sites. Flat model ModEM (FD) results and the DEVA3DMT (FE) topographic model perform similarly. The inversion using ModEM and incorporating topography failed to converge to a meaningful data fit, probably because of the relatively coarse grid that was used to approximate topography.

We compared the forward-modeled responses from three inversion results with the measured data for four sites (see Figure 1). ModEM performed well using a flat Earth model (rms = 1.56); however, the coarse finite-difference grid prevented the inversion incorporating topography from converging (rms = 2.92). The inverted model using DEVA3DMT, which utilizes the FE method to model arbitrary topography, successfully fits the observed data (rms = 1.76). ModEM's performance with respect to topography is likely to improve with a finer model grid (both vertically and horizontally). However, such a refinement would introduce a new set of challenges. Firstly, finer model grids may introduce more anomalies, which are often not adequately supported by data resolution, thus complicating model interpretation. Secondly, refining the model grid in all three dimensions results in a significant increase in inversion run time. Lastly, this refinement necessitates user adjustments to inversion parameters and complicating comparisons between inversion results from different model grids.

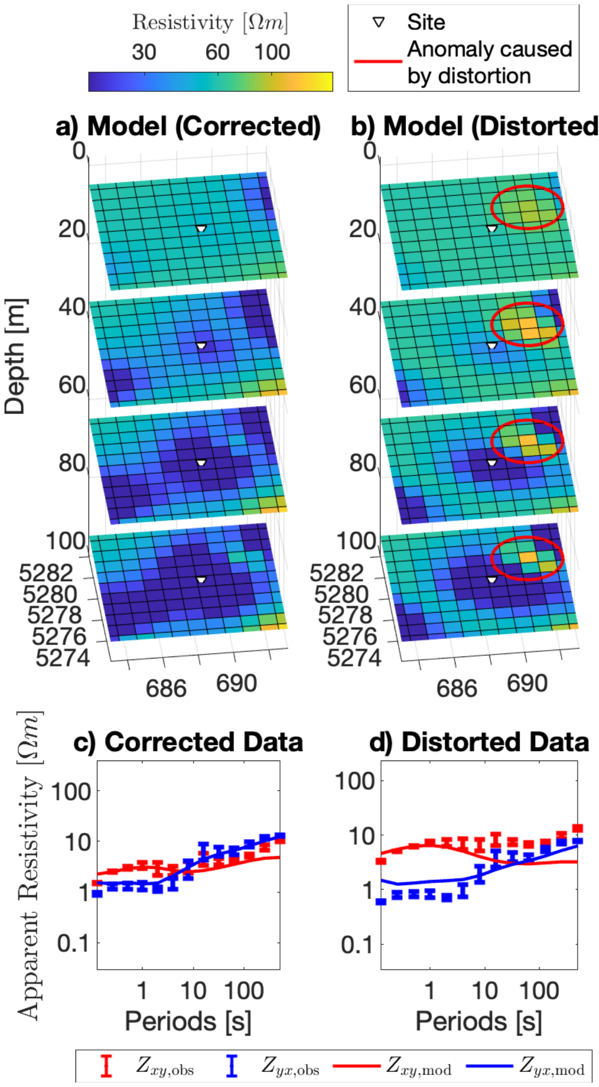

Figure 2: Inversion results of distortion-corrected and distorted data are shown. Panels (a) and (b) illustrate the model between 0 and $100\,\mathrm{m}$ below a strongly distorted MT site. Panels (c) and (d) compare off-diagonal apparent resistivity for observed and modelled data.

We present the resulting subsurface model for both the original and distortion-corrected data around a site exhibiting significant galvanic distortion (Figure 2a and b) as indicated by a twist angle of 22°, a shear angle of 24°, and an anisotropy angle of -4°, as per the notation by (Groom and Bailey, 1989b; Neukirch et al, 2020). It should be noted that the method by (Neukirch et al, 2020) does not account for the scalar gain. We compared the simulated off-diagonal apparent resistivity tensor components with the measured data for both distorted and corrected input data (Figure 2c and d).

The inversion of the corrected transfer functions yields a lower RMS error (rms=1.57) compared to the inversion of the original data (rms=2.28). The original data necessitates the presence of small near-surface anomalies to achieve a fit, whereas the absence of these anomalies in the corrected data inversions suggests that they are artifacts of galvanic distortion. It is important to note that the data fit for the original data is poorer not only for short periods but also for long periods. This indicates that galvanic distortion effects impact not only the near-surface part of the model but also compromise the reliability of deeper sections (not shown here).

CONCLUSION

This study discusses the challenges of topographic variations and galvanic distortion in interpreting 3D MT data based on example of a semi-regional broadband survey in the Baia Mare mining district in Northern Romania. Using ModEM and DEVA3DMT inversion software, we assessed the performance of existing algorithms to account for these effects in a complex terrain and heterogeneous shallow electrical conductivity structure.

The finite-difference modeling method implemented in ModEM performed well on a flat Earth model. DEVA3DMT, using finite-elements for arbitrary topography, successfully fitted the data

Inverting distortion-corrected data yielded a lower RMS error (rms=1.57) compared to the original data (rms=2.28), highlighting the importance of correcting for galvanic distortion for accurate models. Evidence has been shown that galvanic distortion affects both near-surface and deeper sections.

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