Surface geometry inversion of TEM data for thin, dipping conductors

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Summary

We investigate a new method called surface geometry inversion (SGI) for the inversion of transient electromagnetic (TEM) data. Our SGI parameterizes the model in terms of the coordinates of the nodes used to specify the tessellated surface that defines the interface between different geological units. The SGI then inverts for the locations of these nodes. The constructed model directly provides the geometry of the target, which can be more useful than a fuzzy image of conductivity for an exploration project. Our SGI only has the data misfit term in the objective function. A genetic algorithm (GA) is used to solve the over-determined problem in the optimization. We use a finite-element solver with unstructured tetrahedral meshes to solve the TEM forward modeling problem used to evaluate the data misfit of each candidate model in the GA population. We investigate a new parameterization method specifically designed for thin, plate-like structures. We test our SGI and the new parameterization method using a real dataset collected in the Athabasca Basin, Canada.

Keywords: Surface geometry inversion, transient electromagnetic, genetic algorithm, finite-element method

Introduction

Transient electromagnetic (TEM) methods have been widely used in mineral exploration to target graphitic faults (Lu et al., 2021) and volcanogenic massive sulphide deposits (Malo-Lalande et al., 2020) which typically have a thin, steeply dipping structure. In recent years, significant progress has been made in the 3D minimum-structure inversion of EM data and such inversions have seen routine use in exploration projects (Yang et al., 2019). However, it is well known that the minimum-structure inversion algorithms tend to construct models with smooth features when using the l_2 measure of model roughness as a regularization term to reduce the non-uniqueness. The smooth models can be problematic for thin, steeply dipping geological structures commonly seen in mineral exploration projects because the anomalous conductive zone in the constructed model can be many times larger than the true thickness of the thin conductor (Yang et al., 2019). It is therefore difficult to extract the information on the true location of the thin conductor, making it challenging for drill targeting.

We are investigating a different method we call surface geometry inversion (SGI) in an attempt to construct models with distinct boundaries with surrounding rocks. The SGI method can work directly with 3D explicit surfaces constructed based on realistic, arbitrarily shaped geological targets, and the constructed model is consistent with the 3D computer models that geologists use during exploration, which typically use tessellated surfaces to represent the interfaces between different geological units. Our SGI method only focuses on localized anomalous targets whose boundary interfaces are represented by tessellated triangular facets.

Different from previous potential data SGI (Galley et al., 2021), the background physical property model has to be incorporated for TEM problems. The background model can either be obtained from a trial-and-error modeling or from voxel inversion. To deal with thin, steeply dipping conductors, we develop a new parameterization method. Instead of parameterizing the entire outer surface of the target, we only use a triangular surface mesh to represent the center of the plate-like target. We then reconstruct the thin structure from the parameterization surface. To calculate the TEM forward response of each model, TetGen (Si, 2015) is used to automatically generate the unstructured tetrahedral mesh for the entire model once it's built. We then solve the forward modeling problem using a finite-element (FE) solver based on Li et al. (2018).

We use a real-data example from a uranium exploration project to show that our SGI can successfully construct a thin and bending conductor model that matches well with drilling data.

Methods

Model parameterization

We use a bending surface comprised of triangular facets to parameterize thin conductors. As shown in Figure 1, to reconstruct the thin conductor, the surface is first duplicated and then the original and newly duplicated surfaces are moved in opposite directions. The direction is calculated by the average of the normal vectors of all triangles in the original parameterization surface sharing the node. To create a conductor of varying thicknesses at different parts, different distances could be applied when moving different node pairs. Eventually, the two surfaces are sewn together to obtain the thin conductor. During the SGI, we only allow the nodes to be moved perpendicular to the strike of the conductor.

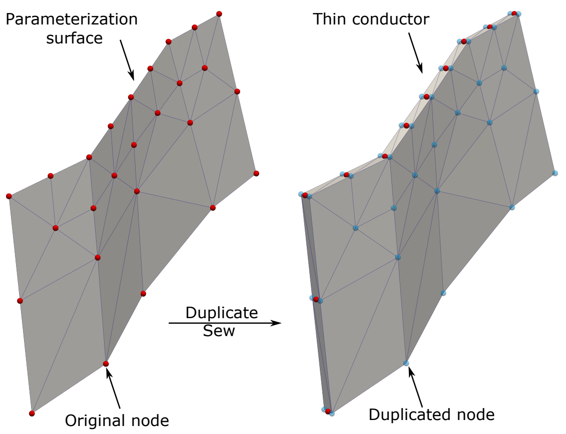

Figure 1: The thin conductor is obtained from sewing the original surface and its duplicate after moving them along the normal direction of the surface.

The physical properties within an anomalous body can also be included as inversion parameters. We subdivide the conductor by simply connecting the four nodes of two edges that correspond to the same edge in the original parameterization surface into two triangles. Afterwards, the number of subdivided volumes becomes equal to the number of triangles in the parameterization surface. We assign a constant physical property value to all tetrahedral cells inside the same volume after the mesh discretization.

Surface geometry inversion

Our inversion minimizes an objective function which only contains a data misfit term. The normalized χ^2 measure of misfit is used here, which can be written as

$$\Phi = \frac{1}{N}\sum_{i=1}^{N}\frac{\left(d_i^{pre} - d_i\right)^2}{{\sigma_{SD}}_i^2}, \qquad (1)$$

where d_i and d_i^{pre} are the ith observed and predicted data, respectively; $\sigma_{SD\,i}$ is the uncertainty assigned to that datum; and N is the number of data. The minimization of Equation 1 is an overdetermined problem as there are typically more data than model parameters for EM problems. Moreover, Equation 1 is significantly non-linear. Consequently, a global optimization algorithm, GA, is used to minimize Equation 1.

To obtain the first generation of the GA population, we randomly perturb the facets' vertices of an input surface model, referred to as the initialization model, within a predefined volume. For real data examples, the initialization model is a best guess of the real Earth and therefore is included in the initial population. The topology of the initial model is preserved while the facets' vertices are changed during the inversion. The volume used to initialize the first generation is called the initialization volume and the volume used to bound new candidate models is called the search volume. The search volume can be different from the initialization volume but here we use the same volume for both.

Example

The Preston Lake Project is a uranium exploration project located just south of the Athabasca Basin in Saskatchewan Province, Canada (Figure 2). In December, 2017, a moving-loop TEM (MLTEM) survey was conducted. Data were collected on six profiles, with a total length of 18 km (Figure 3). A 100 by 100 m transmitter loop was used and the receiver offset was 200 m. In total, 20 channels of three-component dB/dt and B-field data were collected but we only inverted the B-field data. Later, six holes (purple diamonds in Figure 3) were drilled and five holes encountered graphite-bearing fault conductors with a thickness ranging from a few meters to nearly 20 m. The early-time data are noisy, which is possibly caused by a heterogeneous near surface conductivity distribution, so the first eight channels of the measured data are discarded.

The data from L2400E and L3200E were inverted. The data from the stations at either end of the profile were excluded from the inversion as they do not contain information of the conductor. We assigned σ_{SD} as the maximum value of the instrument standard deviation and 5% of the datum plus a noise floor of 0.001

pT. A background conductivity model was obtained from trial-and-error modeling with a model comprising a conductor buried in a layered Earth model.

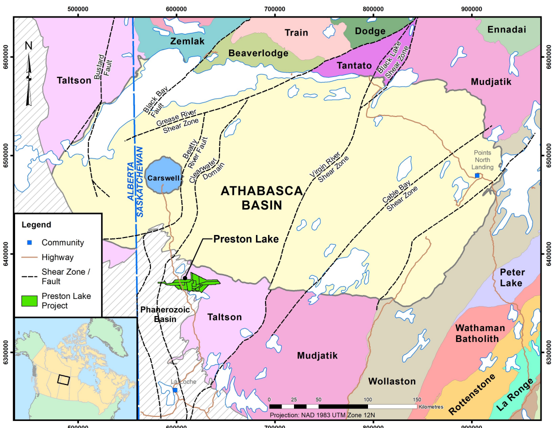

Figure 2: Precambrain geological domain map of northern Saskatchewan, Canada. The Preston Lake Project is located just outside the Athabasca Basin (pale yellow) to the southwest as indicated by the green shaded area (after Lu et al., 2021).

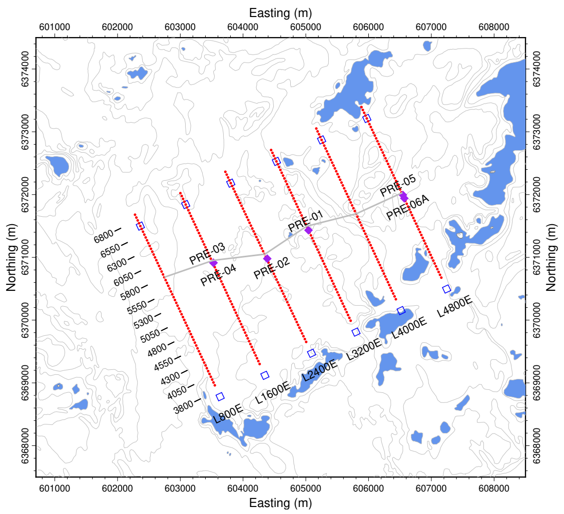

Figure 3: The North Grid of the 2017 MLTEM survey. The blue rectangles represent the first and the last transmitters of each profile while the red dots mark all the receivers in each profile. The purple diamond symbols represent drill holes. The gray line represents the conductor trend.

There were 26 nodes connected into 34 triangles in the parameterization surface (Figure 4). All nodes in the model were only allowed to move perpendicularly to the strike direction estimated from the trial and error modeling. We also inverted the conductivities of different parts of the conductor. In total, the number of inversion parameters was 60 (26 nodes moving perpendicularly to the strike direction plus 34 regions having unique conductivity values).

We ran the inversion on seven computing nodes each with 40 CPUs running at 2.5 GHz. There are 280 MPI processes each with one OpenMP thread. The size of the GA population was 279 and the responses for all the models in the population were being calculated in parallel. The inversion took on average 34.2 minutes for each iteration and the total time for the inversion to finish 200 iterations was about 114 hours.

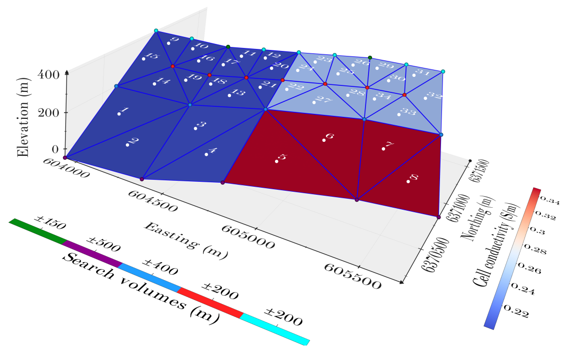

Figure 4: The initialization surface used for the SGI of the Preston Lake data. Each of the triangles is assigned with a fixed conductivity.

The data misfit drops from about 43.8 to 15.9 in 200 iterations (Figure 5). The curve becomes flat after 175 iterations and we consider the inversion has converged. Figure 6 shows the data fitting of Profile L3200E. The data fitting is good in general, except for early-time channels in the inline and vertical components. The relatively worse match between the predicted and observed data for the in-line and vertical components for the first few channels is indicative of an insufficiently accurate background model. This issue can be potentially resolved by using a background model obtained from a voxel inversion instead of trial-and-error modeling. Additionally, we only used a small number of nodes in the parameterization surface, which may be insufficient to represent the subtle features in the real geometry of the conductor.

Figure 7 shows the parameterization surface from the SGI constructed model. The conductor intersects with the graphitic fault at almost the exact true location (the red section of the two color bars used to represent the two drill holes PRE-01 and PRE-02). The good agreement between the constructed model and the drilling data indicates the SGI is successful. The conductor bends to the south and north, respectively, at profiles L2400E and L3200E in the constructed model, which is consistent with the general trend revealed in the MLTEM survey as well as drilling data for the entire grid. The geometry of the conductor stabilizes after about 70 iterations.

Discussion

Compared with minimum-structure inversion, our SGI algorithm requires more computational resources but it can provide constructed models that are more consistent with the kinds of thin, steeply dipping conductors encountered during mineral exploration (and the 3D computer models used by geologists to represent such targets). Additionally, the uncertainty information of the inversion parameters can be obtained via a Markov Chain Monte Carlo sampling method as shown by Galley et al. (2020). Such uncertainty information can be critically important when it comes to drill targeting and risk mitigation. A priori geological information is important for our SGI as it's used to build the initialization model which has a significant impact on the final constructed model. As observed in the example, an inaccurate background conductivity model may cause difficulties for the SGI to fit the entire data set, and constructing the background model from a voxel inversion could potentially solve this issue. Consequently, we consider our SGI as a tool that can be used to refine the geological model at later stages of exploration projects.

Conclusion

We have implemented the surface geometry inversion algorithm for 3D TEM data inversion. Our parameterization method allows for flexible and efficient parameterization of thin, plate-like conductors. The constructed model of the SGI placed the conductor at the correct location according to the drilling data. The geometric information about the conductor is more useful than a fuzzy conductivity image one would get from a minimum-structure inversion, with which drill targeting is difficult.

Acknowledgments

This project is financially supported by National Sciences and Engineering Research Council of Canada and Orano Canada Inc. Digital Research Alliance of Canada (alliancecan.ca/en) and ACENET (acenet.ca) provided the computing resources and invaluable technical advices.

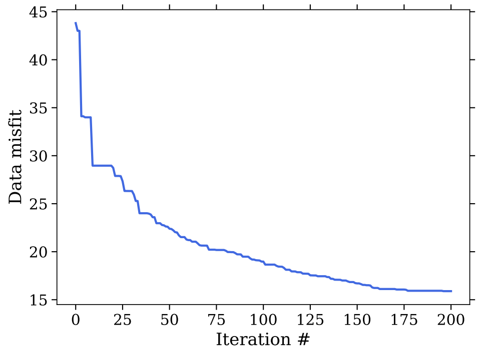

Figure 5: The convergence curve for the SGI of the Preston Lake data.

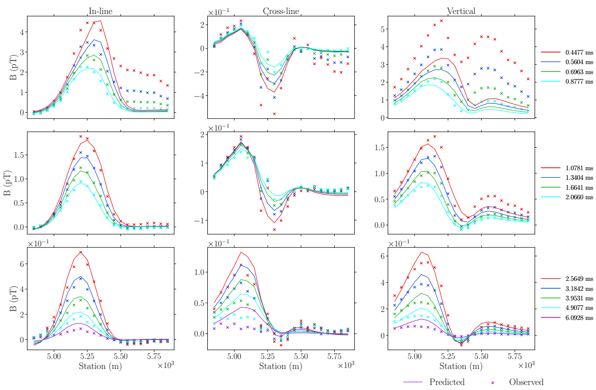

Figure 6: The data fitting of Profile L3200E. The observed data are shown with a cross symbol (x) while the predicted data are shown with solid lines.

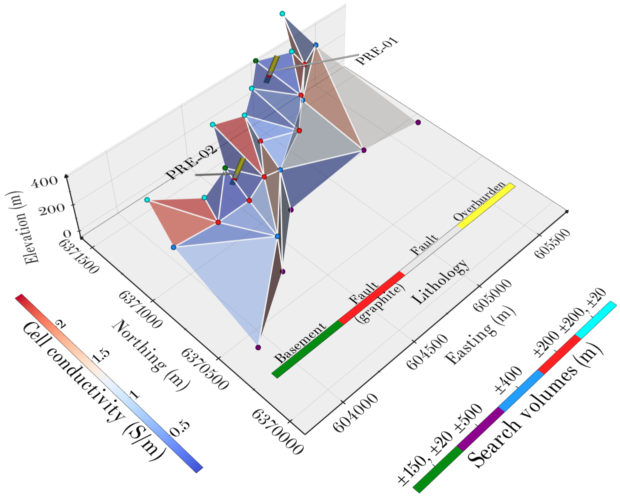

Figure 7: The parameterization surface corresponding to the constructed model of the Preston Lake data SGI.

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