Using finite dipole lengths in complete earth 3D MT modelling

SUMMARY
We have quantified the use of finite electric dipole lengths from the point measurement assumptions typical in 3D MT inversion modeling. Electric fields are measured across dipoles of typically 50 m to 200 m at MT soundings. Modeling algorithms, however, normally use point electric field values at the surface of single cells to calculate MT transfer functions. This is perfectly reasonable for the majority of cases, but there are situations with strong shallow variability of resistivity, where measurements may not be simulated well by point electric fields, and detailed information might not be used optimally. We explore the consequences of this omission by quantifying the difference between point solutions and electric field integrations across dipoles in 3D forward calculations for selected cases. The topic ties closely with galvanic distortion and inversion for related parameters, lateral magnetic field variations, and the benefit of providing shallower constraints for the imaging of deeper targets. As a side product, the analysis led us to focus on the fields output from the 3D modeling, and we illustrate electric current systems through the cases analyzed. We observe that in the presence of strong topography and outcropping inhomogeneities, finite dipole solutions can differ considerably from point solutions, while over a variable regolith case the effect appears more contained.

Key words: Magnetotellurics, topography, dipole, galvanic, distortion, 3D, inversion

INTRODUCTION
Explicit modelling of finite length electric dipoles for MT is not required in most practical cases, and the length and position of the dipoles are customarily ignored. However, in certain scenarios – e.g. in rugged topography, or over a highly conductive overburden – a difference between single point electric field solutions and explicit finite dipole calculations is to be expected. The consideration of finite dipoles in modelling is in itself not new, e.g. both Jones (1988) and Pellerin and Hohmann (1990) integrated fields along electrode positions to study the effect of small scale inhomogeneities on the averaged fields. Watts et al. (2013) illustrated how topography also affects central loop TDEM soundings, showing the limitations for the use of TDEM for MT static shift remedy suggested by Pellerin and Hohmann. In this study, we were motivated by the desire to understand field distortions observed in voltage differences between electrodes, and furthermore we explore whether in the presence of detailed a priori information (LiDAR, drillhole data), differences between point and finite dipole solutions can and should be taken into account in 3D modelling, and how this is best addressed. We have generated a set of illustrative 3D models and have computed transfer functions from the calculated EM fields (examples further to Soyer et al. 2018a). The calculations are performed in two ways: the standard procedure of using fields interpolated to cell surface centres, and the integration of fields along the topographic surface between dipole end points, considering both horizontal and vertical field components.

METHOD AND RESULTS
CGG’s RLM-3D NLCG finite difference inversion suite has been used on hundreds of data sets of different methodologies and for various exploration settings. Originally developed for CSEM and MT/AFMAG, it has been expanded to include potential fields and seismic tomography, and perform joint inversions using cross-gradients (Mackie and Watts, 2012, Mackie et al., 2018, Meju et al., 2018, Soyer et al. 2018b). Recently the 3D TDEM solvers from CGG’s Otze suite (Scholl and Miorelli, 2018) have been integrated into RLM-3D.

Its forward EM solver uses a staggered-grid, E-field formulation, based on the finite integration technique. True magnetic sensor locations are modelled, taking into account the individual positioning of the sensors when calculating transfer functions. RLM-3D can also optionally incorporate an inversion for site-specific MT distortion parameters – real-valued and frequency-independent 2x2 matrices (Soyer et al. 2017 and 2018c). At low enough frequencies, data differences between point electric field solutions and integrations along electric dipoles as in measured data will be in accordance with this distortion model, and may therefore be absorbed into estimated distortion parameters within such joint 3D structure/distortion parameter inversions.

The integration of electric fields is illustrated in Figure 1. In this realization, dipole end points are at cell boundaries. Electric fields are first interpolated from the cell edges to the cell centre, and then integrated component-wise along the topographic path, before being divided by the total length of this path. For a borehole dipole receiver CSEM setup, Patzer et al. (2018) have recently implemented similar field integrations.

Two models are investigated here: (A) a rugged topography scenario, with faulting and strong resistivity variation (Figure 2), and (B) a case of a strongly varying conductive shallow regolith over outcropping basement (Figure 3).

Topography in example A is from a real LiDAR data set. The model was populated with a complex resistivity structure, where a 600 Ωm resistor outcrops to the south, separated by a fault from a layered setting of 300/10/40/600 Ωm to the north. The valley is filled with 3Ωm alluvial sediments, and there are deeper conductive units (not shown). A boxcar smoothing filter was applied to the model for numerical stability.
Modelled response differences are naturally strongest across resistivity boundaries, and assimilate data distortions as often observed in real data and customarily considered as static shift effects. Significant phase differences, i.e. inductive effects, are also observed down to ~10 Hz.

A highly varying conductive overburden of 3Ωm above resistive basement of 1000 Ωm was modelled in example B (Figure 3). The original overburden surface is derived from real drill hole data and was then stretched by a factor of 2 and shifted to shallower depth to simulate extensively outcropping basement. Cell size is 20 m/3m laterally/vertically at the topographic level, which is nearly flat. Very significant changes between single point and finite dipole solutions are found when (1) a dipole extends across the basement-overburden boundary, and (2) in areas where the overburden shape causes the currents to bend, causing very significant distortion (blue detail in Figure 3).

An obvious point to make towards field and modelling procedures is that currents are necessarily travelling along the topographic slope (e.g. Jiracek, 1990). There is a strong electric field in the air but no current, and therefore when finite dipoles are not considered, observed impedances should be scaled to consider only the horizontal component of the dipole distance vector (assuming the code uses horizontal field components only in calculation of impedances). An alternative would be to estimate the field component parallel to the slope directly within the modelling code. For a 45° slope, this results in a factor of about 0.7 for electric fields, and roughly ½ for apparent resistivities.

Furthermore, for accurate simulation, there is clarity needed on what dipole length is used in field procedures when estimating impedance transfer functions – distance along topography, or the line-of-sight distance between the electrodes.

Generally, for incorporation of very detailed shallow structure, fine meshing is required – potentially finer than what is computationally feasible in 3D inversions. A practical way for more accurately modelling the topographic slope and related fields in a finite difference mesh is to calculate equivalent anisotropic resistivities at the topographic boundaries, following a material averaging approach. This has been implemented for the seafloor interface in the marine CSEM component of the RLM-3D code, and an extension for the land MT case is being implemented.

**CONCLUSIONS**

From the finite electric dipole scenarios investigated, we conclude that the difference between single cell and finite dipole calculations is particularly strong for outcropping structure, as expected. For the case of a continuous overburden, effects from dipole extent are weaker, in particular over the thicker parts of the overburden interval. Results from this study provide insight in the dependence of impedance estimates on dipole length in complex 3D settings, further to earlier studies performed on simplified models in flat topography. To include this concept into a 3D inversion procedure, the explicit consideration of finite dipoles would need to be considered also during the calculation of adjoint fields and sensitivities.

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**REFERENCES**


Figure 2. Example A: steep topography from LiDAR (top left), and strong resistivity variation (rotated 3D model view, top centre). Streamlines of currents (top right) at 3 Hz along the marked line (polarization = H_y magnetic east, perpendicular to profile; resistivity in grey scale), with attraction of currents to the conductive valley sediments. Normalized pseudo-sections of dipole vs. point solutions show static effects in apparent resistivity, and phase differences down to ~10 Hz, illustrated also in two example soundings. 100 m dipoles were calculated, at a lateral cell size of 12.5 m.
Figure 3. Example B: varying overburden and outcropping basement; flat topography. Top: streamlines of currents at 60Hz along the shown profile, and on map just beneath topographic (Hy polarization; overburden is shown in grey). Phase difference pseudo-sections of dipole vs. point solutions (bottom left, colour scale as Figure 2). Two areas with strong effects are highlighted: (1) the site marked in orange has Ey-dipole ends in different resistivity environments; (2) at the location marked in blue, currents at this frequency and polarization are WE, and the XY impedance is essentially vanishing. 100 m dipoles were calculated, at a lateral cell size of 20 m.