3D Finite-Element Modeling of Electromagnetic Data with the Open-Source Toolbox custEM 1.0

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We present enhancements and simulation capabilities of the open-source Python toolbox custEM, which was primarily designed for the 3D finite-element (FE) modeling of controlled-source electromagnetic (CSEM) surveys with arbitrary geometries on unstructured meshes. Recently, we extended the capabilities of custEM by implementing multiple approaches for time-domain (transient) electromagnetic (TEM) and magnetotelluric (MT) data.

All modeling approaches rely on the finite-element modeling library FEniCS and the direct solver MUMPS. Of the implemented FE approaches, we prefer the total electric-field formulation using Nédélec basis functions. Further potential and magnetic-field approaches, either as total- or secondary-field formulation, are available as well. Second-order basis functions usually represent a good trade-off between accuracy and computational effort. We support general anisotropic petrophysical parameters, including the conductivity, the magnetic permeability, electric permittivity, and Cole-Cole parameters to simulate induced-polarization effects. We improved all sub-modules of custEM which enabled more robust, accurate, and computationally efficient simulations. It is well-known that solving 3D FE systems with direct solvers demands plenty of memory (RAM). Though particular simulations might require up to a few TB RAM, most geometries can be handled on computer architectures with a few tens of cores and about 250 GB RAM. In addition, reusing the factorization of the system matrix significantly accelerates the solution of problems with multiple right-hand sides which is beneficial for multiple transmitters, time-domain approaches using the implicit Euler or rational Arnoldi methods, or the computation of sensitivities.

We present simulations for the three fields of electromagnetic modeling to demonstrate the accuracy and computational performance of custEM. The CSEM example is motivated by multi-frequency semi-airborne surveys as conducted in the DESMEX project. A 3D LOTEM example serves to compare three different 3D time-domain modeling approaches. The most recent support for magnetotelluric data is demonstrated by comparing our solutions of the Dublin test model 1 with those provided by the community. These and further examples are available in the code repository and can be reproduced independently. In combination with the automated online-documentation of the source code, the variety of provided modeling example can help interested users to gain first experiences in custEM. Our implementation can support the community in forward modeling studies, inverse modeling applications, cross-validations, as well as
understanding or teaching purposes.