SCUBAS: A python-based numerical model to estimate electrical surges in submarine cables during geomagnetic disturbances

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Submarine cables have become a vital component of our modern infrastructure. They carry a significant amount of international internet traffic, so any disruption to their operation would have wide-ranging consequences. However, it is uncertain how modern submarine cables systems would behave in an extreme (1 in 100 years) space weather event. Thus, submarine cables, like other critical infrastructure, need to consider space weather as High Impact, Low Frequency (HILF) events which require an assessment of risk and preparation of mitigation action if necessary. The aim of this study is to build a computational model of geomagnetic induction to calculate the induced voltages produced in submarine cables during geomagnetic disturbances. We present the theory for estimating the induced voltages experienced by the submarine cables during geomagnetic disturbances and then describe implementation of a Python-based software model to be used by end-users, such as researchers or cable engineers. The model requires the specification of a number of parameters, such as Ocean/Earth conductivity model, ocean depth, length of cable sections, and then uses magnetic observatory data to estimate the induced cable voltages. As part of the demonstration of the capabilities of the software and validation of the model, we describe several applications and examples of the software simulation results.

Introduction

- During geomagnetic disturbances, geomagnetic field variations induce electric currents in the Earth and long conductors, commonly referred to as geomagnetically induced currents (GIC).
- Geomagnetic induction first affected telegraph systems and widespread problems occurred during the Carrington event of 1859 [1–3].
- Recordings on the trans-Atlantic TAT-8 cable during a major magnetic storm in March 1989 showed that the cable's power feed could be affected during extreme geomagnetic disturbances [4].
- The aim of this study is to build a computational model of geomagnetic induction to calculate the induced voltages produced in submarine cables during geomagnetic disturbances.
- We describe 1) the input and output formats, 2) the internal working of individual computational blocks, and 3) their interconnectivity.

Methodology: Computational model

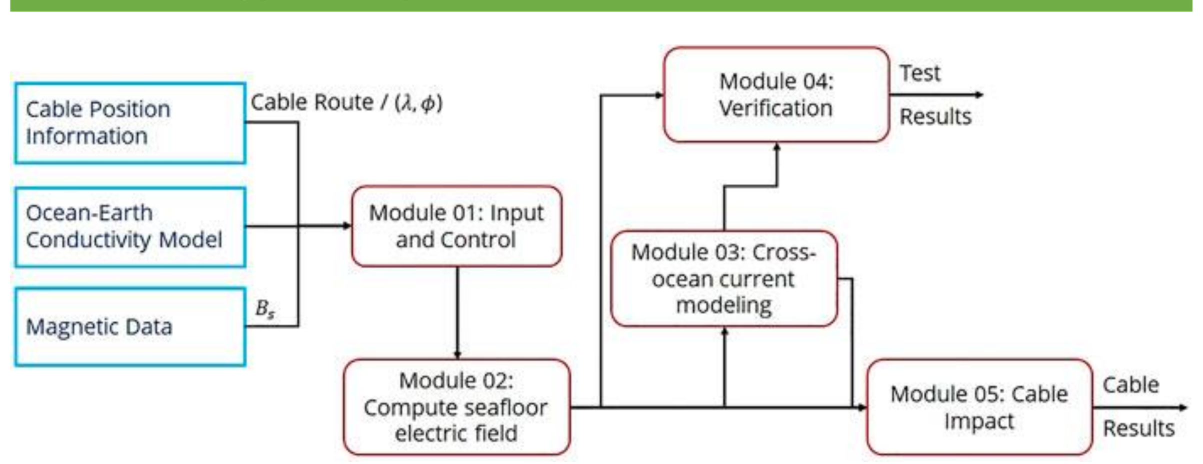

Figure 1. Control flow diagram of operations done by computational model. The boxes in red and blue define operational and input modules, respectively. Solid lines represents data flow interconnections between different modules.

Methodology: Computational model

Module 01: Input and control

The operation of the program is governed by the Input and Control Module. A Route Position List (RPL) file, containing location of the cable section edges, is used to find geometry and conductivity structure along the cable. The ocean depth (d) along the path of the cable profile can be viewed and the user can specify how the cable route will be broken into sections that will be used in the subsequent modeling. Conductivities of each layer then form a predefined table.

Module 02: Seafloor electric field calculations

The calculations of seafloor electric fields are comprised of two parts: 1) calculate the transfer function, T_x, between the seafloor electric field and the surface magnetic field variations, and 2) use the transfer function with magnetic field data to calculate the seafloor electric fields [5].

$$T_x = \frac{E_f}{B_s} = \frac{Z}{\mu_0}\frac{2}{\left(1+\frac{Z}{Z_d}\right)e^{kd} - \left(1-\frac{Z}{Z_d}\right)e^{-kd}}$$

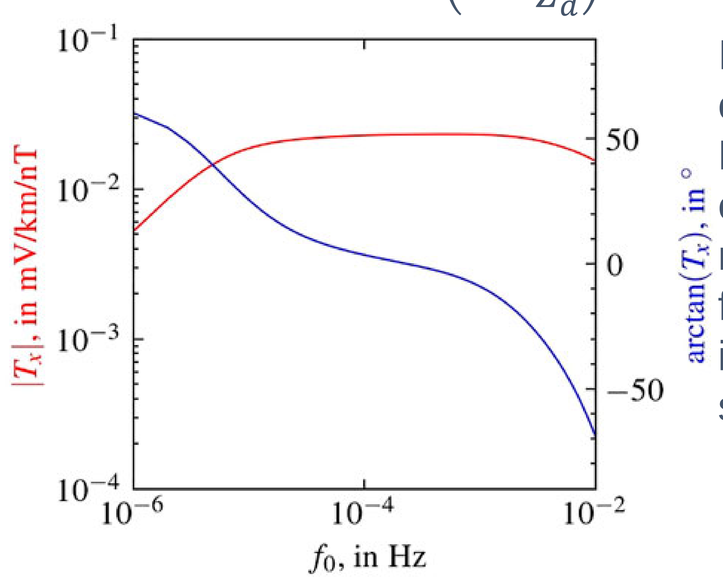

Figure 2. Amplitude ($|T_x|$) and phase (arctan (T_x)) of the transfer function, T_x.

Induced emf along any cable laying on the Earth is superposition of emf induced by northward and eastward fields. Hence, the induced emf on j[th] section

$$E_j = e_j^N L_j^N + e_j^E L_j^E$$

Module 03: Cross-ocean current modeling

The Earth potentials produced can be modeled using distributed source transmission line (DSTL) theory as shown by Wang et al. (2022). The potentials at each node, in vector U, are then obtained by matrix inversion of the admittance matrix, Y, and multiplication by the nodal current sources

$$U = Y^{-1}J$$

These potentials at the edges of each section between nodes i, k are then used to calculate the Earth potential along the cable route:

$$U_{i,k}(x) = \frac{U_k\left[e^{\gamma x} - e^{-\gamma x}\right] + U_i\left[e^{\gamma(L-x)} - e^{-\gamma(L-x)}\right]}{e^{\gamma L} - e^{-\gamma L}}$$

Module 04: Verification

We used synthetic magnetic field and analytical solutions to validate the numerical simulations (refer to Figures 3-5).

Module 05: Cable impact

For a cable route that is divided into S sections (in Module 01), the emfs calculated for each section [Eq. 2 in Module 02] are summed to give the total emf induced in the cable:

$$E_c = \sum_{j=1}^{S} E_j$$

Simulation Results

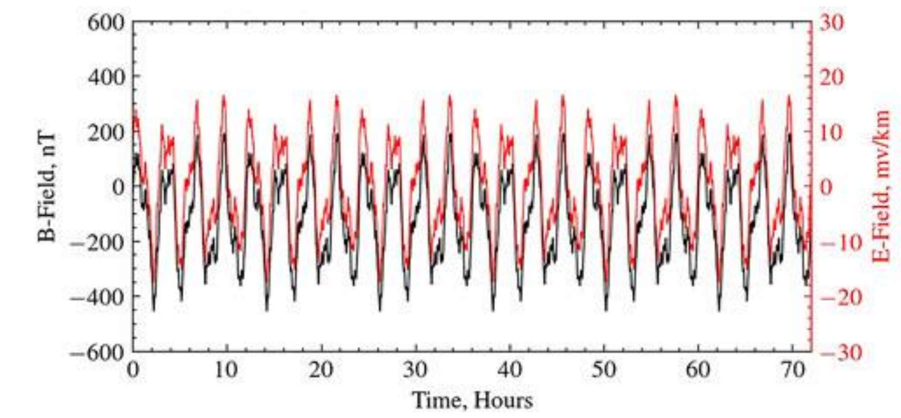

Figure 3. Synthetic magnetic field variations (in black) and analytic electric field solution (in red).

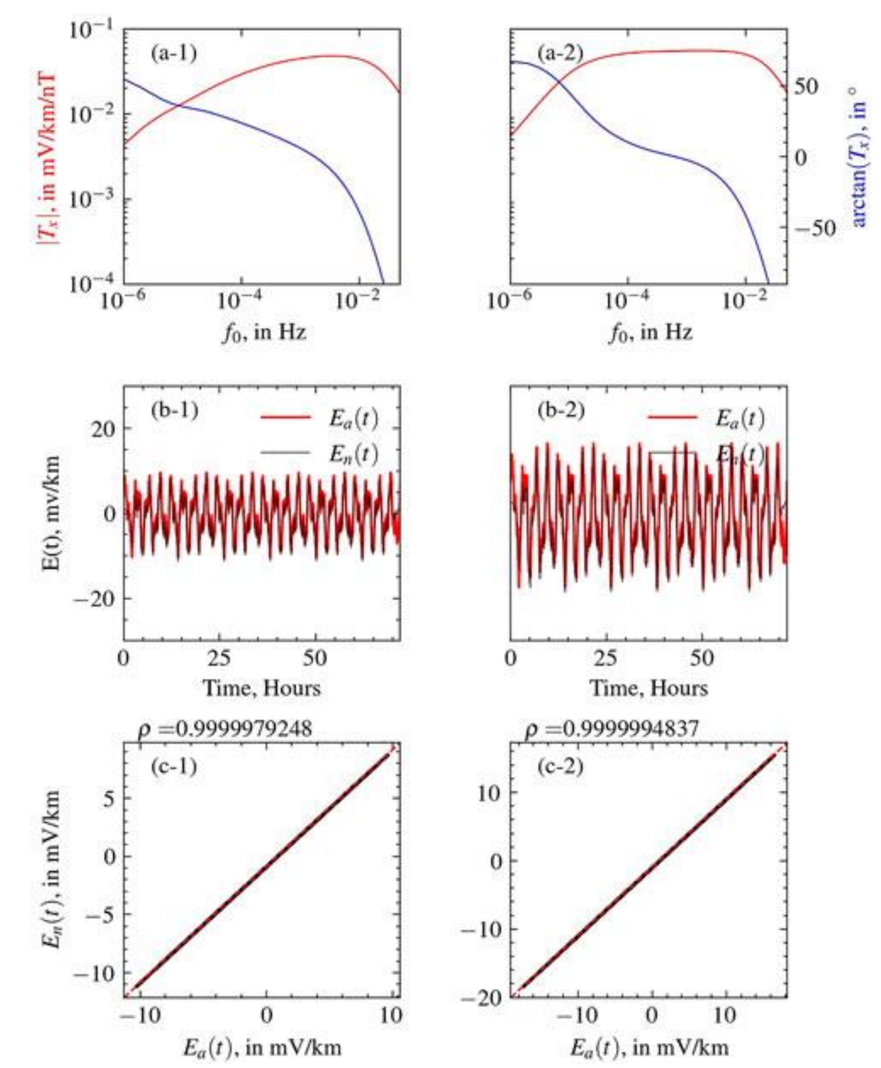

Figure 4. Model validation using following layered Ocean-Earth conductivity models: 1) Uniform and 2) Atlantic model. From top to bottom rows present: (A) Amplitude and phase spectrum of the transfer function, Tx. (B) Time series of analytically (red) and numerically (black) estimated induced electric field. (C) Correlation analysis between analytically (Ea(t)) and numerically (En(t)) calculated induced electric field. The correlation coefficient (ρ) between Ea(t) and En(t) is provided in the top left corner of the panel.

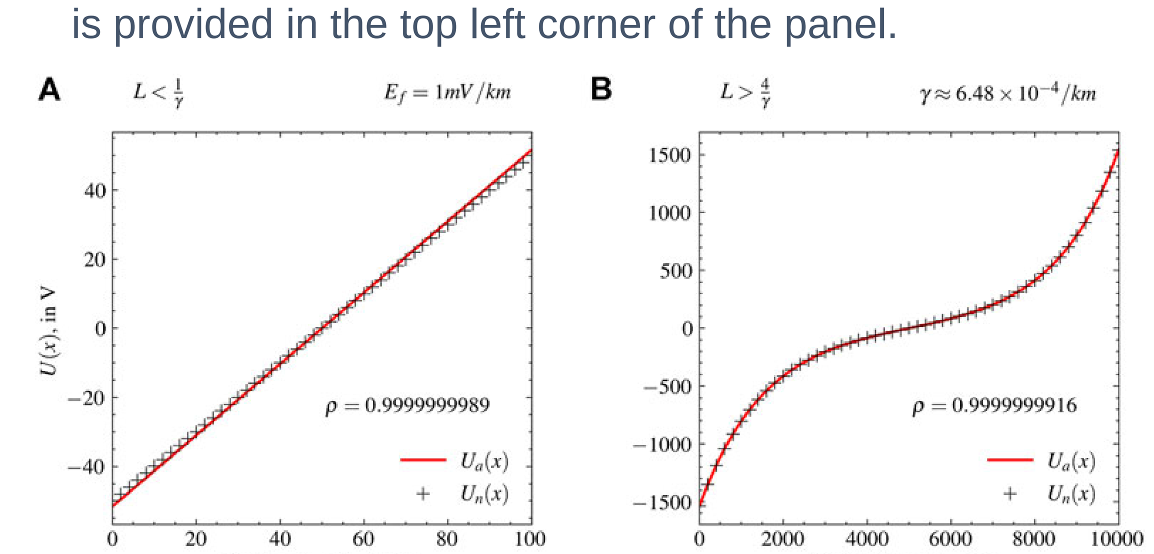

Figure 5. Distribution of voltage, estimated using theoretical approximation (red) and computational model (black "+"), along the (A) electrically-short and (B) electrically-long Ocean-Earth sections. The correlation coefficient between theoretical and numerical estimates are provided in each panel. L and 1/γ are the physical length and adjustment distance of the cable, respectively.

Summary & Conclusion

- We present a computational model to estimate the geomagnetically induced electric field and voltage in submarine cables, including calculation of the transfer function relating the seafloor electric field to the surface magnetic field variations. Cross-ocean modeling describes a way to estimate induced voltage along the submarine cable due to the seafloor geoelectric field.
- We validated the model calculation processes by comparison of model results with analytic solutions for two different Ocean-Earth conductivity models and electrically-long and electrically-short Ocean-Earth sections.
- The model can be used to study the effects of different types of geomagnetic phenomena including Sudden Storm Commencement (SSC), storm main phase, substorms etc.

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The datasets used in this study are synthetically produced inside the code and can be found in the GitHub and it is also pip installable '**pip install scubas**'.

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