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MODELING OF SOURCES IN THE TIME DOMAIN - PRACTICAL EXAMPLE WITH VERTICAL-VERTICAL CONTROLLED-SOURCE ELECTROMAGNETIC METHOD

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ABSTRACT. The challenge in transient method modeling is, precisely, to simulate the response of the fading of the electromagnetic field (EM) and its interactions with the subsurface in the face of physical property contrasts. The study herein displays the result of the time domain modeling of the vertical-vertical controlled-source electromagnetic method (VVCSEM), written in Python, looking to analyze the responses of electromagnetic fields in different models and configurations while not requiring significant knowledge of scientific programming or financial resources for proprietary software licenses. A canonical geological model was used to analyze the field behavior. The codes were published under a permissive open-source license and made available on the Zenodo platform and GitHub repository. The VVCSEM modeling using Jupyter notebooks (Anaconda) proved accessible, efficient in detecting proposed resistive anomalies, as expected, and reliable, compared to the literature descriptions.

Keywords: transient; simulation; Python; VVCSEM.

INTRODUCTION

Historically, modeling was analog, which was quite limiting regarding the time used to prepare the modeling and the failure to represent physical phenomena in the subsurface, something inherent to the methodology itself. With the evolution of programming languages and the improvement of computational capacity, which made machines capable of performing calculations and approximations that are not always analytically available, building geophysical models has become more efficient. Thus, currently, the evaluation of geophysical methodologies through computational models spares relevant resources, helps in formulating the best strategies to study targets of interest, aids in evaluating the feasibility of using specific acquisition techniques, and helps in understanding waves and field behavior.

In the case of electrical and electromagnetic computational modeling, the difficulties are the mathematical formulations that describe the events that one wants to represent/analyze, as well as the behavior of the field, its components in different media, and, mainly, the transient behavior in measurements. With that in mind, several professionals and companies have been dedicating their research to elaborating and improving codes in different languages and platforms.

All this research resulted in numerous works developed over the years. This specific work is a contribution focused mainly on showing how the analysis of electromagnetic field behavior can be conducted even when lacking an excellent knowledge of scientific programming (Fortran) or avoiding monetary costs with applications with proprietary software. In addition, a time domain method was used because it is still an obstacle for many, most being more familiar with frequency-domain methods.

The algorithm used in this manuscript was written in the Jupyter notebook, in Anaconda (Anaconda, 2017), produced from routines contained in the modeling example of the marine controlled-source electromagnetic method (MCSEM) made on empymod (Werthmüller, 2017) and let available on GitHub. Empymod is a modeler for electrical and electromagnetic sources developed in Python. The program mentioned here for the vertical-vertical controlled-source electromagnetic method (VVCSEM) takes advantage of the electromagnetic field solution in a canonical model (Constable and Weiss, 2007), changing the source (Tx) from dipole to bipole, frequency domain to time domain (Fast Fourier transform - FFT and Hankel), source and receiver orientation (Rx) from horizontal to vertical, and finally the electromagnetic field (EM) component from Ex to Ez.

Anaconda Navigator is a free distribution platform for Python programming. In Anaconda, the codes are built (or imported from modules) and compiled in the same substrate where the figures are plotted (matplotlib). Moreover, it provides a user-friendly interface, reduces the processing time, and speeds up the computational capacity since it uses the very own resources of any internet browser, not needing to install compilers and graphics processors.

The code produced and described in this manuscript is published under a permissive open-source license and made available on the GitHub repository and Zenodo platform. The code can be accessed at https://github.com/danusamayara/vvcsem and at Souza et al. (2022), which are the GitHub and Zenodo addresses.

GitHub is a repository of codes and routines written mainly in Python, and the Zenodo platform is a multidisciplinary repository used for sharing and making available the results of various types of research.

This manuscript will go by the physical principle that, through approximation, it is possible to express the electric and magnetic fields as a response to the impulse of simple models in terms of ordinary and extraordinary functions. The electric and magnetic fields can be expressed in a semispace's frequency and time domains. When the model contains more than one conductive layer, it is impossible to describe the electric and magnetic fields in the frequency or time domain using ordinary and extraordinary functions. However, it is possible to express the fields as integrals of ordinary and extraordinary functions, provided that the limits are flat and parallel surfaces of infinite extension. For a better understanding of modeling techniques, see Key (2009).

Some study methods that use subsurface property measurements over time intervals are complicated to model, such as the mnemonic transient method, the induced polarization, and the VVCSEM. Readings and data collection are performed when the source is inoperable (power off), but the geological environment is still excited by the stimulus of the recently turned-off source.

The challenge in modeling transient methods is to simulate the EM field fading response and its interactions with the underground environment against contrasts in physical properties.

The VVCSEM method was used to exemplify the transient modeling, strictly speaking, an MCSEM method that uses a vertical electric dipole as a source, vertically oriented receivers, and a time domain acquisition mode. The main application of VVCSEM is in reservoir monitoring, reducing ambiguities encountered by conventional seismic and minimizing exploration risks in fields with complex geology.

VVCSEM modeling using Jupyter notebooks (Anaconda) proved accessible, efficient in detecting the proposed resistive anomalies, and reliable, compared to the literature descriptions.

METHODS

VVCSEM

Well-regarded by substantial studies for the direct indication of hydrocarbons (Sainson, 2012), MCSEM had its acquisition configuration altered to improve vertical resolution and promote a more significant distinction between conductive and resistive bodies (Holten et al., 2009a; Frafjork et al., 2014). In addition to instrumental changes, the methodology received the mnemonic nomenclature of VVCSEM. TEMP-VEL was patented (Transient Electromagnetic Prospecting with Vertical Electric Lines - Gloux and Holten, 2009).

VVCSEM performs subsurface electromagnetic field measurements in a marine environment. The transmitter comprises a DC pulse generator, a vertical electric dipole, consisting of two steel electrodes (3000 A each) connected by an extensive copper cable, having one electrode 50 meters below the ship and a second electrode on the seabed, and an electrode launcher/recoverer. The receivers are vertical tripod antennas produced in nonferrous material and spread across the ocean floor in radial lines (to Tx). More detailed instrumental information can be found in Barsukov et al. (2007), Barsukov et al. (2008), and Kjerstad (2010).

Data acquisition occurs in the time domain, in which both the source and the receivers are static. Data reading by the receiver is conducted during source inactivity, and the transmitter pulse is described as a P8 Thue-Morse sequence (Figure 1).

The turned-off source is, mathematically, a scaled version of H(-t), and for that, H(t) is the Heaviside function (Helwig et al., 2019). Since the source is triggered when the receivers are turned off, the data do not suffer interference from direct waves and airwaves, which are inherent drawbacks of SBL acquisitions.

Figure 2 presents an illustration of two periods of the P8 sequence.

Figure 3 clarifies the method better (Flekkoy et al., 2009; Holten et al., 2009b). Figure 3 shows a VVCSEM data acquisition scheme in which a stationary submerged source (VED) oscillates between on and off periods. At the

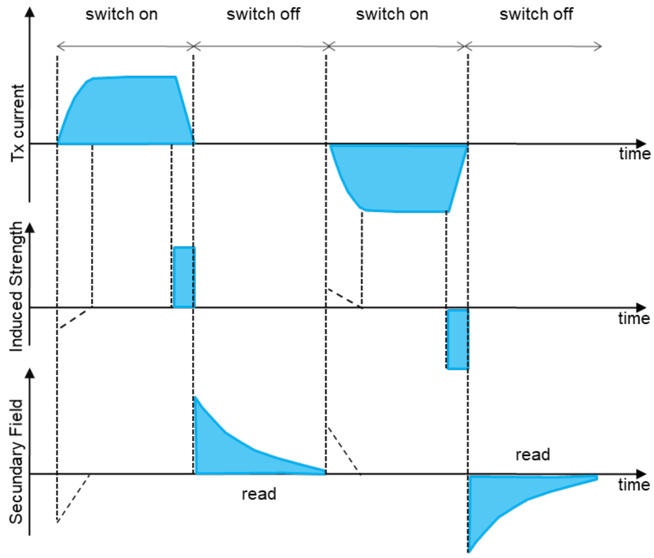

Figure 1: Tx pulse behavior during data acquisition.

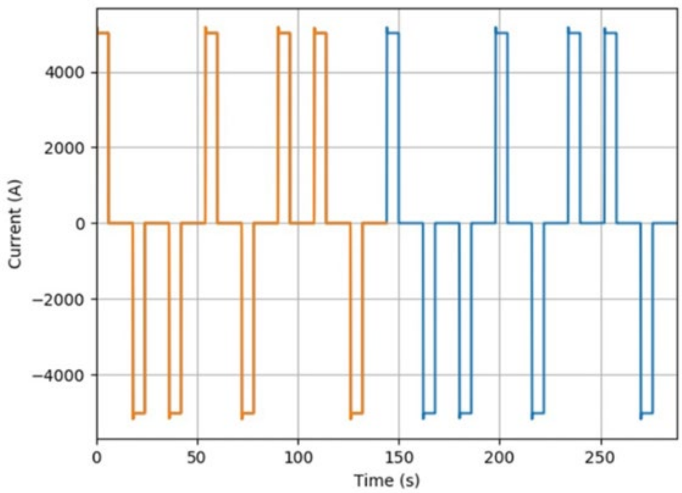

Figure 2: Illustration of two periods of the P8 sequence (Helwig et al., 2019).

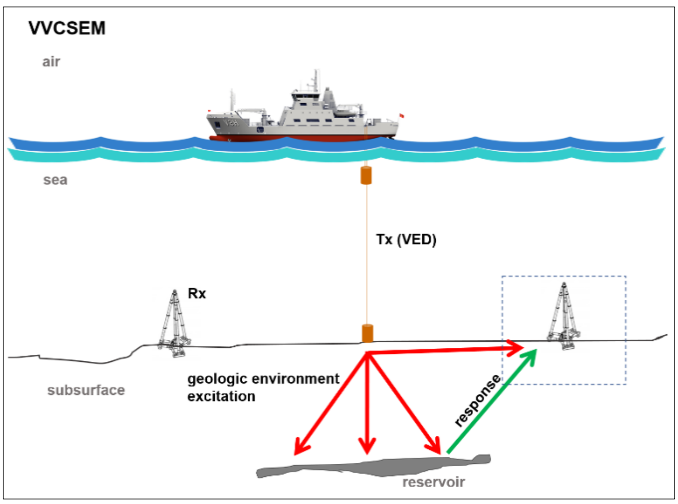

Figure 3: VVCSEM data acquisition scheme.

same time, the pulse is captured by the receivers scattered on the ocean floor in moments of source inactivity.

The vertical-vertical arrangement (Tx and Rx) only causes propagation of the TM mode (magnetic transverse Hy, Ex, and Ez components) of the EM field. The short offset creates a near zone of the imaging since the usual distance from Rx to Tx is 250 m (followed by multiples). Even though the received signal is weak, due to the reading being done only when the source is turned off, there is a higher sensitivity to electrical resistivity vertical contrast.

The VVCSEM method is, strictly speaking, an MCSEM method that distinguishes itself from the SBL (Seabed Logging – a method that became synonymous with controlled source EM methodologies) due to its source-receiver arrangements and acquisition mode (time).

The exploratory activity involves several factors that are not controlled, such as the presence/absence of oil and the quality of the exploited product. The VVCSEM method has gained prominence mainly for technological and operational innovations to minimize the uncertainties and ambiguities found throughout oil and gas. In addition to increasingly presenting a shorter acquisition time and higher resolution, it provides much information and knowledge about the geological environment of interest.

The code in the time domain

The Python language was chosen to build modeling in the time domain, considering its simple reproduction and open-sources. According to IEEE Spectrum analysis, Python is intuitive and has several published libraries (Esmaili, 2021), and it is also the leader in ranking among high-performance languages (Cass, 2021).

Empymod is an electrical and electromagnetic source modeler developed in Python. The scripts have versions in either Jupyter notebook (editor/compiler within Anaconda) or IPython, QT, and PyCharm consoles.

In the empymod modeler, it is possible to calculate the electrical or magnetic responses due to the excitation of a 3-D electromagnetic source in a layered Earth model with vertical transverse isotropic resistivity (VTI), VTI electrical permittivity, and magnetic permeability from very low frequencies (DC) to very high ones (GPR). The field calculation is performed in the wavenumber-frequency domain, and Hankel and Fourier's transform is included to obtain the answers in the space-frequency and space-time domains.

Layered models have a finite number of horizontal interfaces and are bounded by semispaces at the top and bottom. Each layer is horizontally unlimited. The fields decay toward infinity in all spatial directions, which can be seen as the radiation conditions. These conditions are incorporated into the physical solutions that one wants to find. In these cases, it must be assumed that there is no outside interference in the modeled region. This can be done by imposing radiation conditions outside the computational domain. This method is used in modeling integral equations in which the system matrix is already full. Furthermore, it can also be done by extending the model boundaries in a way it becomes far enough apart so that nonphysical boundary conditions can be imposed.

These strategies are used with finite-difference modeling techniques, finite elements, and finite integration, in which the system matrix is large but sparse. Another problem is discretization; in direct modeling, the distribution of conductivity values in space is known, and the boundaries between regions where these values differ can be followed.

Finite volume and integral equation techniques can be used to generate discrete systems of equations on the finite element. However, if it was assumed that the limits coincide with changes in conductivity values, the choice should be made when unknown discrete field values are positioned on the grid. Since electric and magnetic fields have continuous tangential components across a boundary, it is logical to locate them on the edges by connecting the grid points on the mesh and orienting them along these edges.

In finite difference methods, a rectangular mesh is typically used, and the three components of the vector are located at nodal points of the mesh. This strategy reduces the ability to follow boundaries in the model and satisfy the boundary conditions.

Starting from Maxwell's equations in the time domain in a semispace:

$$\nabla \times e + \mu_0 \frac{\partial h}{\partial t} = 0 \tag{1}$$

and

$$\nabla \times h - \varepsilon_0 \frac{\partial e}{\partial t} = 0 \tag{2}$$

where e is the electric field (V/m); h is the magnetic field (A/m); μ_0 is the magnetic permeability (4π x 10^{-7}); and ε_0 is the electrical permittivity (8.85 x 10^{-12}). The laws of Faraday and Ampère are used in the material world,

$$\nabla \times e + \frac{\partial b}{\partial t} = -j^m \tag{3}$$

and

$$-\nabla \times h + \frac{\partial d}{\partial t} + j = -j^e \tag{4}$$

where b is the magnetic induction (Wb/m^2 or Tesla); d is the dielectric displacement (C/m^2); j^e and j^m are the external electric and magnetic current density volume, respectively.

The finite element methods are very similar to the finite integration technique (see Clemens and Weiland, 2001) but are based on variational principles. Their formulation should be made only in a domain below the soil surface.

The method starts with the transformation of equations (3) and (4) to the frequency domain, obtaining:

$$\nabla \times E - i\omega B = 0 \tag{5}$$

and

$$\nabla \times H - j = j^e \tag{6}$$

moreover, assuming the definition of a grid with connected cells, the finite element method is based on replacing a continuous boundary problem with a discrete one. The region of interest is subdivided into simple elements (triangles, for example), and the Galerkin method is applied to each element.

Transient data can be obtained by computational models at a sufficient number of frequencies using the fast sine transform by irregular logarithmic frequency axis sampling optimized with interpolation and fast Fourier transform (FFT), or by using the logarithmic FFT (FFTLog). Notice that the optimized logarithmic frequency axis, an irregular sampling method with interpolation, can also minimize the frequencies for which complete models must be computed for fast sine transformation and logarithmic FFT. More information can be found in Rijo (2007).

The VVCSEM modeling code consists of five files; three are core modules containing input checks and other utilities and filters containing the FHT (Fast Hankel Transform) filter coefficients. The routines are (1) kernel, in which the wavenumber calculation is performed; (2) transformation, in which the Hankel and Fourier transform is computed; and (3) model, which contains the model routines produced by end-users.

The main modeling routine is bipole, which calculates frequency and time domain responses for arbitrarily oriented, electrical, or magnetic bipolar sources and finite-length receivers.

The calculation in the domain of the wavenumber in the kernel follows Hunziker et al. (2015) and calculates the full wavefield for a layered VTI model. The code does not limit the model: the source and receiver can be placed anywhere, inclusive in the first or in the last layer, and to define whether the first layer is aired or not aired. Bipoles can cross the boundaries of layers. Information about depths, frequencies, and the configuration of the source-receiver must be entered, and each layer is characterized by its ρ_h horizontal resistivity; λ electrical anisotropy, in which $\lambda = \sqrt{\rho_v/\rho_h}$; the vertical and horizontal magnetic permeability, μ_v and μ_h; vertical and horizontal electrical permittivity, ϵ_v and ϵ_h. Time domain calculus and arbitrary rotated finite bipole models are performed using Fourier transforms (NumPy solver).

All filters published in Key's source codes (Key, 2009; Key and Ovall, 2011) are included in the routine, including the Key's and Anderson-Kong's filters.

The electric dipole moment (at the origin of the coordinate system) is defined as:

$$p = e_x\ I(t)\ ds\,\delta(r), \tag{7}$$

where e_x is the unit vector of the dipole axis; $I(t)$ is the transient pulse; ds is the dipole length; and $\delta(r)$ is the Dirac delta function.

A rectangular pulse signal of current with decay in time can be described by:

$$I(t) = \frac{1}{2t_1}\left\{(1 - e^{-\omega_p t})\ H(t) - \left(1 - e^{-\omega_p (t-2t_1)}\right)H(t-2t_1)\right. \tag{8}$$

where $H(t)$ is the step Heaviside function; $2t_1$ is the width of the original rectangular pulse, and $\tau_p = \frac{1}{\omega_p}$ is the rise time, which is considered equal to the decay time.

The electric field in the plane z = 0 and perpendicular to the axis of the dipole is the dipole moment:

$$E_x(\rho,t) = \frac{\mu_0 \alpha I(t) ds}{16\pi t_1}\begin{cases} 0,\ t = 0 \\ E(\rho,t),\ 0 < t < 2t_1 \\ E(\rho,t) - E(\rho,t-2t_1),\ t > 2t_1 \end{cases} \tag{9}$$

with

$$E(\rho,t) = -\frac{e^{-R^2}}{t\sqrt{2t}}\left\{\frac{1}{2R^3}[F(R) - F(R)] + \frac{\Omega}{R^2}G(Z) - \frac{2\Omega^2}{R}F(Z)\right\}, \tag{10}$$

$$F(Z) = \mathrm{Re}\left[e^{Z^2}\mathrm{erfc}(Z)\right], \tag{11}$$

$$F(R) = \mathrm{Re}\left[e^{R^2}\mathrm{erfc}(R)\right], \tag{12}$$

$$G(Z) = \mathrm{Im}\left[e^{Z^2}\mathrm{erfc}(Z)\right] \tag{13}$$

$\mathrm{erfc}(Z) = \frac{2}{\sqrt{\pi}}\int_Z^\infty e^{\lambda^2} d\lambda$ being the complementary error function and $Z = R + i\Omega$, $R = \frac{a\rho}{\sqrt{2t}}$, $\Omega = \sqrt{\omega_p t}$, $a = \sqrt{\frac{\mu_0 \sigma}{2}}$, $\rho = \sqrt{x^2 + y^2 + z^2}$. This solution is valid for the condition $\sigma >> \omega_p \varepsilon$.

For the solution to this problem, Maxwell's equations in terms of the magnetic potential vector A are written as

$$\mu\varepsilon \frac{\partial^2 A}{\partial t^2} + \mu\sigma \frac{\partial A}{\partial t} + \nabla \times (\nabla \times A) = 0. \tag{14}$$

RESULTS

Surveys using the VVCSEM method are carried out in a control area with no reservoir or resistive anomalies and other profiles on interest areas. Thus, the results are displayed in comparative graphs between the curves obtained in the regions with and without hydrocarbons.

Similar to real prospects, numerical simulations compared the contrast between the presence and absence of hydrocarbons. The canonical geological model (Constable and Weiss, 2007) consists of layers with different depths and resistivities. The transmitter is a dipole the size of a water line (reduced 50 m), and the receiver is a one-off, located 250 m in the Y direction of the Tx, as shown in Table 1.

Table 1: Canonical model.

Layer	Depth (m)	Resistivity (Ωm)
air	-∞ - 0	2.0e14
sea	0 - 1000	0.33
overburden	1000 - 2000	1.0
HC	2000 - 2100	100.0
under burden	2100 - ∞	1.0

The modeling performed in Anaconda solved the electric field (Ez) equations in the frequency domain and, after Fourier transforms, in the time domain. The response of the field behavior was plotted, considering the canonical model with and without the reservoir. The code was validated from the recreation of the response obtained by Holten et al. (2009a) and Helwig et al. (2013), illustrating the methodology's performance in different source-receiver arrangement configurations.

The modeling satisfactorily recovered the publication's response by Helwig et al. (2019). As seen in Figure 4, the modeling was able to simulate the behavior of a transient vertical electric dipole (VED) and identify the resistive layer proposed in the canonical geological model. The blue dotted line (NoHC) represents the field response to the subsurface without the reservoir, and the red solid line (HC) represents the response to the substrate with a reservoir.

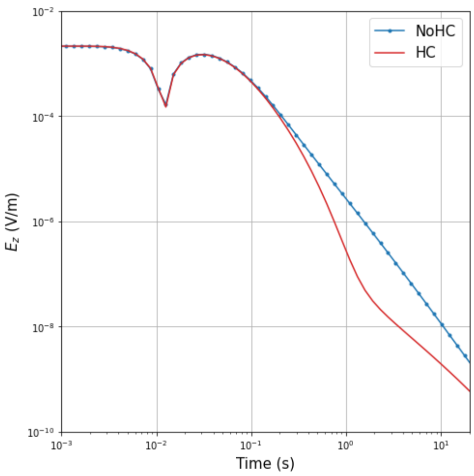

Figure 4: VVCSEM modeling response to the parameters described in Helwig et al. (2019).

Based on Figure 4 and consistent with the literature, the presence of the resistive body causes the field to decay more rapidly, creating the difference between the two curves.

The model based on Helwig et al. (2019) was built using the same model, but the receivers were changed to positions 200 m (blue solid line), 423 m (orange dotted line), 894 m (green dashed line), 1891 m (red dot-dashed line) and 4000 m (purple solid line with plus signs) away from the Tx in the X direction (Figure 5).

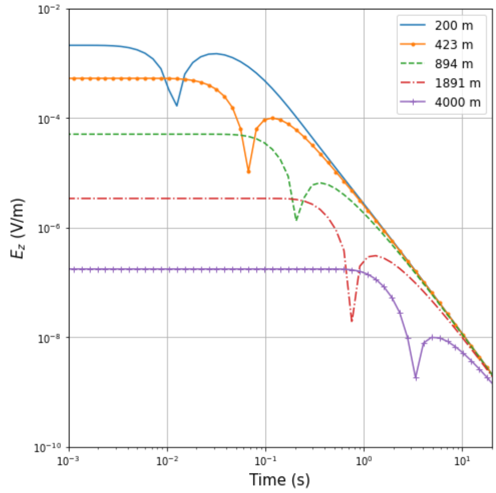

Figure 5: VVCSEM modeling response to the parameters described in Helwig et al. (2019).

Analyzing Figure 5, it can be noticed that the greater the separation between Tx and Rx, the longer it takes to record the field response. The curve begins to present discrepancies between the positive and negative values of the field since the Ez field response is plotted in absolute terms.

According to the given model proposed in Helwig et al. (2019), the modeling once again satisfactorily recovered the answer. The curve behavior for a transient VED with different offsets was reliable.

The code allows for several tests, such as seawater slide thickness variation and stratification of its electrical resistivity (variable with temperature and depth), variation of the reservoir layer (thickness, tilt, and resistivity), and many other source-receiver configurations.

CONCLUSION

The VVCSEM response in surveys is usually contaminated with induced polarization (IP) information due to acquisition patterns. However, these do not hinder the objective of differentiating the anomaly generated by the resistive body.

Numerical modeling provided good results for the proposed model. Python has proven to be a very effective tool in analyzing the behavior of electromagnetic fields in different situations and acquisition modes.

The VVCSEM program satisfactorily recovered the publications' responses, both in the curve behavior for a transient VED and in the identification of the resistive layer.

It was emphasized that modeling might not reflect the reality because the computational simulation approximates fields and wave behavior. For example, in the case of methodologies such as VVCSEM, responses should always be validated with publications in indexed journals.

In future studies, it is intended to use and compare emg3D (Werthmüller et al., 2019), SimPEG (Heagy et al., 2017), PETGEM (Castillo-Reyes et al., 2018), and custEM (Rochlitz et al., 2019) to implement the solution to solve the 3-D EM field propagation in the time domain. In addition, it is intended to build a long-term inverse modeling code for VED.

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SOUZA, D.M.: adapted the time domain empymod code according to benchmark literature and designed the models; wrote the manuscript; **SILVA, M.W.C.:** suggested different models and VVCSEM configurations; revised the manuscript; **SOUZA, V.C.T.:** developed the code and simulations. All authors contributed to the interpretation and discussion of the results and improvement of the models.

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