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Curupira V1.0: Joint Inversion of VES and TEM for Environmental and Mass Movements Studies

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Abstract

An innovative inversion code, named "Curupira v1.0", has been developed using Matlab to determine the vertical distribution of resistivity beneath the subsoil. The program integrates Vertical Electrical Sounding (VES), successful in shallow subsurface exploration and Time Domain Electromagnetic (TEM) techniques, better suited for deeper exploration, both of which are widely employed in geophysical exploration. These methodologies involve calculating subsurface resistivity through appropriate inversion processes. To address the ill-posed nature of inverse problems in geophysics, a joint inversion scheme combining VES and TEM data has been incorporated into Curupira v1.0. The software has been tested on both synthetic and real-world data, the latter of which was acquired from the Parana sedimentary basin which we summarise here. The results indicate that the joint inversion of VES and TEM techniques offers improved recovery of simulated models and demonstrates significant potential for hydrogeological studies.

Keywords

VES, TEM, Joint Inversion, CRS—Controlled Random Search, Paraná

Sedimentary Basin, Brazil

1. Introduction

The inversion process in geophysics is a challenging task due to the ill-posed, ill-conditioned nature and non-uniqueness of the solutions for recovering model parameters from field-acquired data. To mitigate these issues, employing multiple geophysical methods simultaneously can improve the ambiguities mentioned above. This approach involves integrating results from different geophysical methods to construct an overarching model. One way to accomplish this is through joint inversion or data fusion, which generates a single model compatible with multiple data sets. In this work, we focus on Vertical Electrical Sounding (VES) and Time Domain Electromagnetic (TEM) methods, which share the same property of exploring vertical resistivity distribution in the subsoil.

For decades, both VES and TEM techniques have been widely used in the geophysical community for various investigative purposes. VES is more effective for detecting resistivity targets near the surface, while TEM is capable of penetrating deeper conductive structures in the subsurface using transmitter loops spanning tens of meters. However, for a successful combined picture of the subsurface there are incompatibilities between the techniques. VES measures apparent resistivity in terms of AB electrode spacing (meters), while TEM soundings relate resistivity to response times (seconds). Therefore, a computational technique that can handle both data sets simultaneously, often denoted joint inversion, is essential.

The literature contains several approaches to joint inversion in geophysics. Works like those by [1] [2] [3] demonstrate how joint inversion of TEM and magnetoteluric (MT) soundings can enhance model parameters compared to separate inversions. Other researchers, such as [4] and [5], applied joint inversion of Direct Current (DC) and TEM to map coastal aquifers and identify saline/freshwater interfaces. [6] and [7] used joint inversion of Induced Polarization and resistivity to delineate earthflow structures and prevent torrential surges. [8] employed joint inversion of apparent conductivity and magnetic susceptibility to characterize buried targets using EM38 frequency domain equipment.

In this paper, we introduce an innovative Matlab program capable of performing both separate and joint inversions of resistivity and TEM data using the "Controlled Random Search" (CRS) algorithm. An interactive option to introduce numerical errors into the data has also been included for algorithmic testing. The program, Curupira v1.0 [9], was validated with synthetic and real data in [10] and has been widely applied across various locations in São Paulo state, Brazil [11]-[16]. It has also been used for academic purposes at different universities and research institutes. In this paper, we present examples of previously research results and real data acquired in the Paraná sedimentary basin, located in the region of Bebedouro, São Paulo State (Brazil), in order to showcase the capabilities of the program that can be used in various environmental studies.

2. Numerical Modeling

Before exploring the joint inversion of Vertical Electrical Soundings (VES) and Transient Electromagnetics Soundings (TEM), we first outline the ideas behind each numerical model specific to the individual geophysical method. For VES, the forward solution employs digital linear filter theory, as proposed by [17]. In the case of TEM, the forward problem relies on filters developed by [18] and elaborated upon by [19]. Both forward models for each case are discussed in the following subsections:

2.1. VES Numerical Modeling

The concept of linear filtering for the numerical solution of electrical methods was originally developed by [20] and [21]. This approach enables the calculation of apparent resistivity at a low computational cost, an essential feature for efficient code. The method entails solving the resistivity function integral through convolution. This resistivity transfer function is then convolved with a pre-calculated set of filters, resulting in the computed apparent resistivity. The accuracy of the linear filters used for this calculation has been significantly improved over time, as reported by [17]. For a more comprehensive understanding of the mathematical calculations and theory behind resistivity transformation in layered media, readers are referred to [22].

2.2. TEM Numerical Modeling

For 1D forward modeling of TEM, we begin with the magnetic field generated by a vertical dipole in a layered medium, each layer having distinct resistivities and thicknesses. To generate this magnetic field, a large transmitter loop is placed on the ground, within which an induced current flow. This current is abruptly turned off, and an apparent resistivity is computed as a function of time using a receiver loop located at the transmitter loop's center. Over time, the induced currents penetrate deeper layers, achieving greater depths. The relationship between depth and resistivity will depend on the subsurface conductivity distribution. Detailed schematics of the layered model and its operation can be found in the works of the [19] [23] [24].

3. Inversion Algorithm

For more than 80 years, direct current (DC) and Time Domain Electromagnetic (TEM) methods have been employed to map the distribution of resistivity in the subsoil. These techniques have gained popularity due to their low acquisition cost and the ease of data collection. After data is gathered in the field, it must undergo a validation process before moving on to the inversion step. The final objective is the interpretation of these results.

Current approaches to solving the inversion problem primarily utilize either local gradient-based methods or global optimization methods (GOMs). In the first case, gradient methods facilitate a quick descent to the nearest minimum but are dependent on a good initial model [25]. In the second scenario, random searches are conducted in the model space until a global minimum is achieved. Unlike gradient-based methods, GOMs don't require an initial model but are more time-consuming. This computational cost has limited the application of GOMs mainly to one-dimensional (1D) problems in geophysics, and less commonly to two-dimensional cases.

The concept of 1D joint inversion of electrical and electromagnetic data was initially explored by [26]. They found that integrating both methods led to more accurate reconstruction of the physical properties under investigation than using each method separately. Extending this line of research, several studies have touted the benefits of using joint inversion in VES and TEM data [1] [2] [3], primarily employing gradient-based methods for the inversion process. More recently, [27] compared gradient methods and GOMs, finding more promising results with the latter in terms of mapping the resistivity distribution in the subsurface. However, they noted that GOMs took longer to compute than local or gradient-based methods, and that the latter required good initial models for solution convergence.

In this work, to offset the computational cost disadvantage and to capitalize on the absence of a need for strong initial models, we propose using a Controlled Random Search (CRS) algorithm for carrying out the inversion. This algorithm, introduced by Price [28], is considered a local method with a random search feature that doesn't rely on gradient or derivative calculations. Its strategy starts from an initial point and then creates a random path; the step size and direction are controlled by a function that considers successful directions found in previous iterations. The CRS algorithm has been integrated into our Matlab program, which offers a range of features for performing both separate and joint inversions of VES and TEM data. Additionally, the program gives users the option to add or omit errors in the data, useful in cases of synthetic data simulation. The subsequent section will detail the program's full capabilities and the features of its user interface.

4. Software Operation

The Curupira program was developed to serve as a versatile tool for tasks related to Vertical Electrical Sounding (VES) and Transient Electromagnetic (TEM) surveys in the form of a central loop. The program is capable of performing numerical modeling for both methods, individual and joint inversion, and also has the capability to conduct numerical modeling with added synthetic errors. These features distinguish Curupira as a unique program, as it encompasses all of these options within a single software package.

The program offers a range of nine distinct operations, which can be described as follows:

1) Noise-free VES Modeling
2) Noise-free TEM (Central Loop) Modeling
3) Noise-free Simultaneous Modeling of Both Methodologies
4) Individual VES Inversion
5) Individual TEM Inversion
6) Joint VES/TEM Inversion
7) VES Modeling with Noise
8) TEM (Central Loop) Modeling with Noise
9) Simultaneous Modeling with Noise of Both Methodologies

4.1. Noise-Free VES Modeling

The Noise-free VES Modeling operation involves the simulation of Vertical Electrical Sounding (VES) data without any noise or interference, enabling a pristine representation of subsurface electrical responses. An example is provided in **Figure 1(a)**, illustrating a synthetic model consisting of five layers. This approach holds significance in various contexts, encompassing educational purposes as well as the analysis of everyday scenarios. In an educational context, this software plays a pivotal role in illustrating VES curves and how they evolve in response to changes in layer count, thickness, and resistivity. Such analyses provide insights into the behavior of hidden or equivalent layers. In practical daily applications, noise-free VES modeling proves invaluable in the planning of field campaigns, allowing for an assessment of the feasibility of reaching desired depths or specific targets. When coupled with the inversion algorithm, and when paired with synthetic models' apparent resistivity curves, it becomes a powerful tool for scrutinizing the possibilities of detecting thin layers, equivalent layers, or deep subsurface structures.

4.2. Noise-Free TEM (Central Loop) Modeling

In this operation, we conduct noise-free modeling of Transient Electromagnetic (TEM) data using a central loop configuration. Similar to the previous case, this type of software finds extensive utility in both educational contexts and everyday applications. With TEM, the program can simulate various transmitter loop sizes, effective coil receiver areas, and measurement durations. **Figure 1(b)** serves as an illustration of the TEM forward calculation for the identical synthetic model, comprising five layers, that was employed in the VES forward calculation. The analytical possibilities afforded by this tool are highly intriguing, revealing, for instance, the effects on early-time responses with larger loops or highly conductive shallow layers. It also highlights the consequences of imbalanced parameters at the start of measurements, transmitter loop size, and resistivity of shallow layers. Furthermore, it allows for an assessment of the advantages of larger effective area receiver coils. Just like in the previous case, when

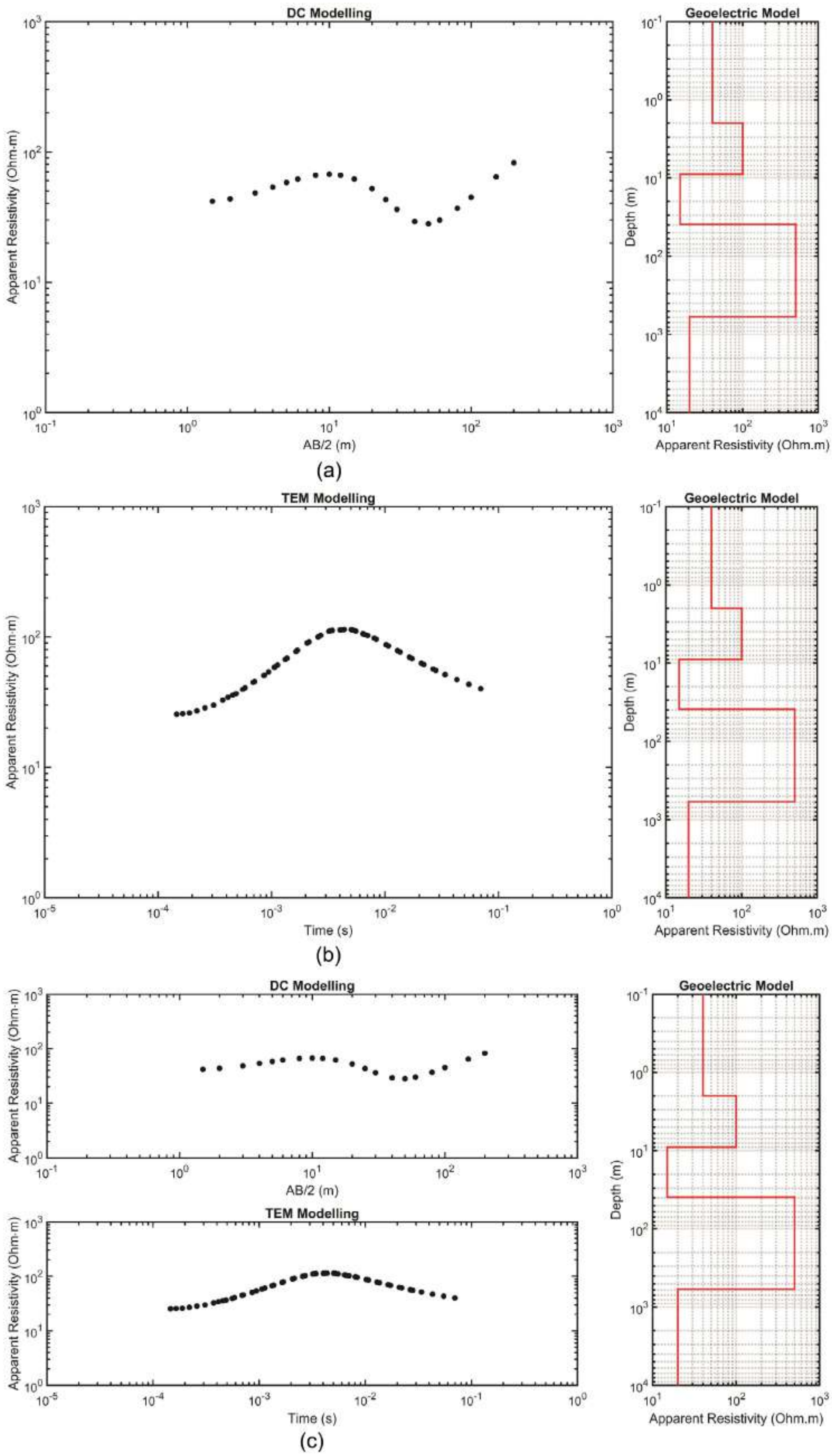

Figure 1. Noise-free Modelling. In (a) the forward calculation for the VES case, in (b) forward calculation for TEM sounding and in (c) the results for the simultaneous modelling of both methodologies.

this tool is coupled with the inversion algorithm, it opens up a vast array of possibilities for different feasibility studies related to target detection and depth investigation. This facilitates more efficient field planning with equipment and configurations tailored to the specific challenges at hand.

4.3. Noise-Free Simultaneous Modeling of Both Methodologies

This operation facilitates the simultaneous and noise-free modeling of both VES and TEM methodologies, offering a comprehensive perspective on the distinct responses of both methods. **Figure 1(c)** displays the outcomes of the two forward calculations (VES and TEM sounding) using the same model as in the previous cases. The calculations performed in this option do not deviate from those in the previous options. The difference lies in the presentation of results on a single graph rather than separate ones. However, having both apparent resistivity curves visualized on the same graph allows for a swift comparison of how the two methods perceive the subsurface differently. Furthermore, conducting apparent resistivity curve calculations for the same model enables both individual and joint inversions of the two methodologies. This proves valuable in enhancing our understanding of the potential of combining these methods for more robust subsurface analysis.

4.4. Individual VES Inversion

In this operation, the program undertakes a dedicated inversion process for VES data, with the sole objective of estimating subsurface properties and structures exclusively from VES measurements. This approach offers an additional avenue for VES inversion, and it stands out as a robust algorithm, characterized by its global search capabilities. Unlike some local optimization techniques, which might converge towards suboptimal solutions (local minima), a global search algorithm explores a broader solution space, making it highly robust. This robustness is a critical advantage, as it minimizes the risk of falling into convergence traps that could compromise the accuracy of the inversion results. The software has found extensive applications, such as the example depicted in **Figure 2(a)**, showcasing a VES data acquisition carried out in a landslide-prone area within Campos do Jordão city, São Paulo State, Brazil. Additional findings in a region susceptible to mass movements are detailed in [29].

4.5. Individual TEM Inversion

In this process, the program concentrates on individually inverting Transient Electromagnetic (TEM) data, with the primary objective of estimating subsurface characteristics and structures solely based on the TEM measurements. TEM data inversion software with global search algorithms is not as widely available as in the case of Vertical Electrical Sounding (VES), and especially those equipped with global search algorithms are relatively scarce. While not the only approach of its kind, individual TEM inversion remains less common in practice. **Figure 2(b)** illustrates the TEM sounding inversion utilized in a study focused

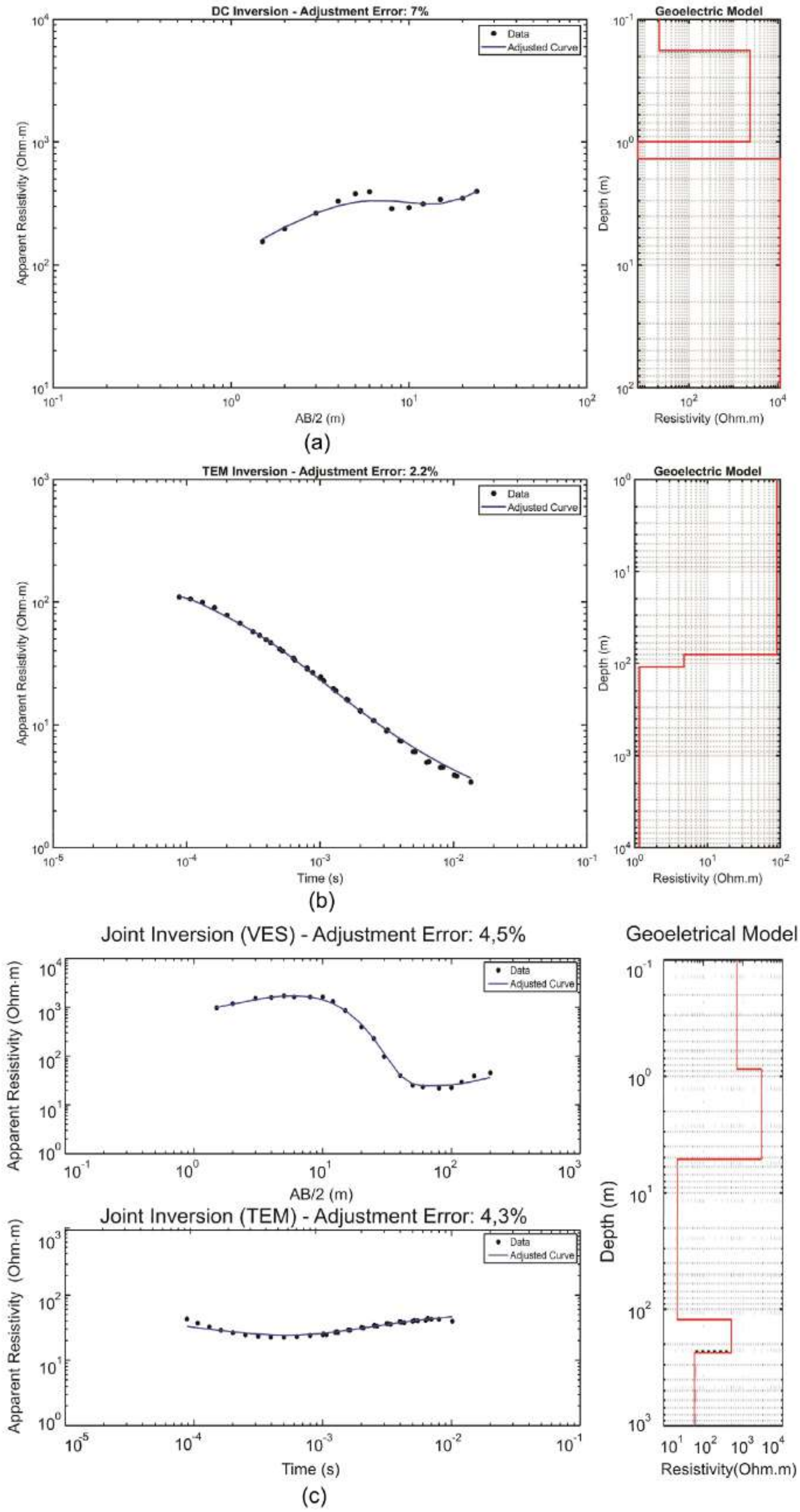

Figure 2. Individual and joint inversions. In (a) the forward calculation for the VES case, in (b) forward calculation for TEM sounding and in (c) the results for the simultaneous modelling of both methodologies.

on the application of the TEM method in an urban setting. This study was conducted in the heart of São Paulo city, located in São Paulo State, Brazil [30].

4.6. Joint VES/TEM Inversion

This operation combines both VES and TEM data to perform a joint inversion. This is the main tool of the software. Because it allows the integration of methods, something unconventional. The joint inversion of Vertical Electrical Sounding (VES) and Transient Electromagnetic (TEM) sounding offers several advantages in subsurface characterization and geological investigations. This integration provides a more complete picture of the subsurface, leading to a better understanding of geological structures and properties [31] [32]. Another important aspect is the improved Depth Resolution, once VES and TEM have different depth sensitivities. VES is typically more sensitive to shallow depths, while TEM can probe deeper into the subsurface. When combined, they provide improved depth resolution across a wider range of depths, allowing for a more accurate depiction of subsurface features.

Also, with the joint methodology is possible to reduce ambiguity, because geological models derived from individual VES or TEM inversions are more suitable to suffer from ambiguity. Joint inversion helps to reduce this ambiguity by constraining the interpretations with data from both methodologies. This results in more reliable subsurface models. Joint inversion allows for cross-validation between the two datasets. If the interpretations from VES and TEM are consistent and agree with each other, it provides greater confidence in the derived subsurface model. In cases where inconsistencies arise, they can be examined to identify potential errors or uncertainties in the data. **Figure 2(c)** depicts an example of the joint inversion method applied in Urupês city, situated in São Paulo State, Brazil. The study conducted by [33] provides insights into the practical application of this joint methodology for responsible groundwater exploration.

4.7. VES Modeling with Noise

In this operation, the program performs VES modeling while incorporating noise, simulating real-world conditions and providing a more robust understanding of subsurface properties. Utilizing VES modeling with added noise offers several distinct advantages. Firstly, it enhances the realism of the model, providing a more accurate representation of subsurface electrical responses in real-world conditions. Overall, incorporating noise into VES modeling enhances its accuracy and usefulness across various scientific and practical contexts. In **Figure 3(a)**, is present the forward calculation of the same model with added noise, which was initially presented in the noise-free case. As observed, in the case of VES, the noise is randomly distributed, as described by [10].

4.8. TEM (Central Loop) Modeling with Noise

Similar to the previous operation, this one involves TEM modeling with the

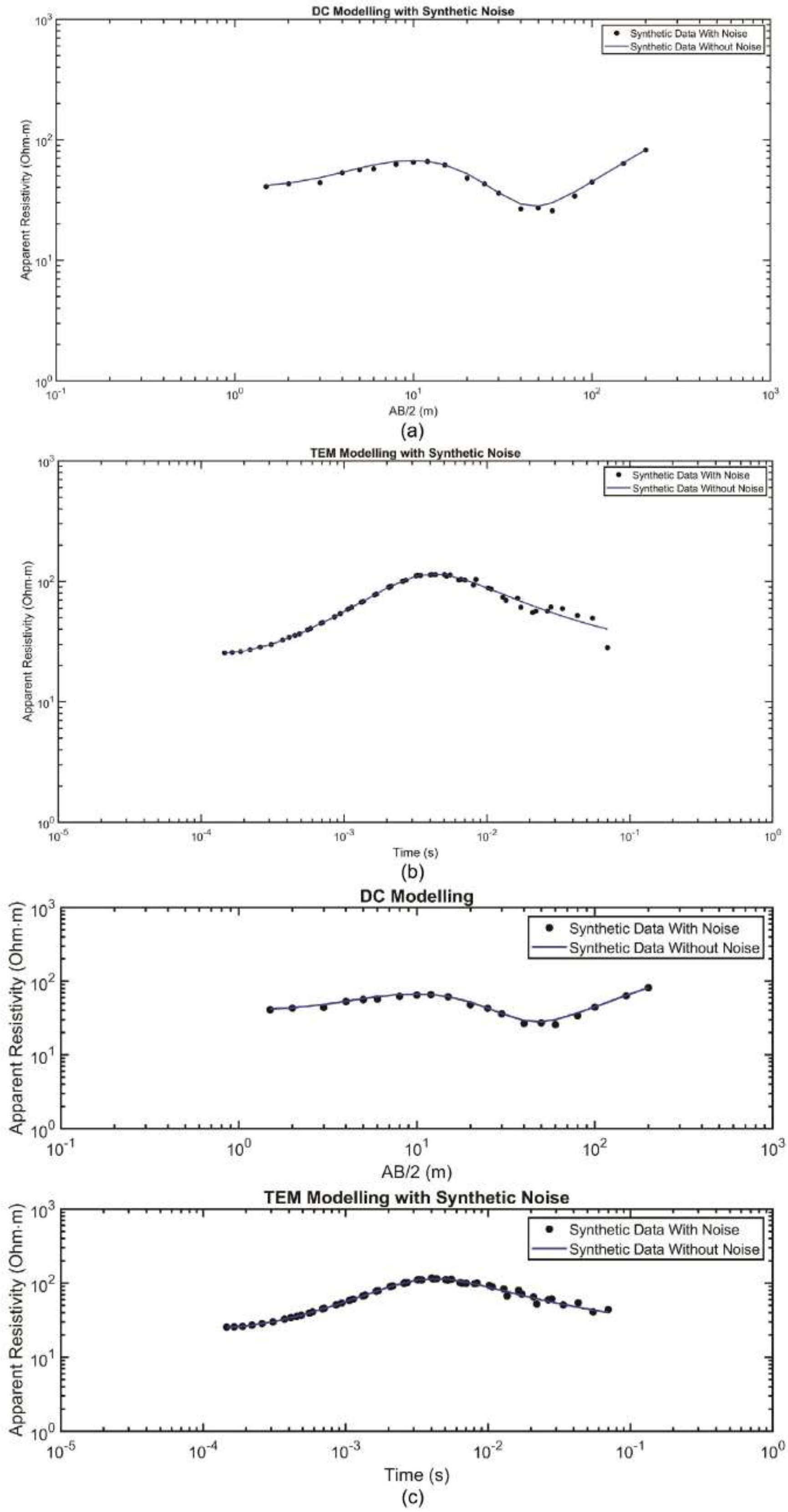

Figure 3. Modeling with noise. In (a) the forward calculation with added noise for the VES case, in (b) forward calculation with noise for TEM sounding and in (c) the results for the simultaneous modelling with added noise for both methodologies.

addition of noise, making the simulations more representative of actual field conditions. Incorporating noise into Transient Electromagnetic (TEM) modeling brings forth several notable advantages. It facilitates a more realistic exploration of electromagnetic responses, making it valuable for both educational purposes and practical applications. When coupled with inversion algorithms, noise-inclusive TEM modeling widens the scope for feasibility studies related to target detection in large depth of investigation, enabling more efficient fieldwork planning with tailored equipment and configurations. In the case of TEM sounding (**Figure 3(b)**), the noise becomes more apparent during the later times, primarily because the signal weakens as it penetrates deeper layers. The mathematical expression outlining how the noise is incorporated can be found in [32].

4.9. Simultaneous Modeling with Noise in Both VES and TEM Methods

In this scenario, the program performs simultaneous modeling of both Vertical Electrical Sounding (VES) and Transient Electromagnetic (TEM) methodologies, taking noise into account. This approach allows for a comprehensive comparative analysis, under realistic conditions, of how both methods appears different under the effect of noise, a critical aspect for practical applications. Once the results are ploted in a single graph. Illustrated in **Figure 3(c)** is an example showcasing the contrasting noise characteristics in both cases.

5. Real Case Use

The city of Bebedouro is located in the São Paulo State of Brazil, within the Paraná Sedimentary Basin. The local stratigraphy consists of a Cretaceous sedimentary cover made up of the sandstones of the Bauru Group [34] and [35]. This is overlaid by Late Cretaceous basalt layers and Jurassic sandstones of the Botucatu Formation, which houses the Guarani Aquifer [36]. VES and TEM soundings were conducted in two distinct areas of the city: the Andes and Botafogo districts.

In both the Botafogo and Andes areas (**Figure 4** and **Figure 5**), individual VES inversion identified the shallow layers—comprising soil and Bauru sandstone—as well as the top of the Serra Geral basalt layer. In both locations, the VES individual inversion determined that the top of the basalt layer was at a depth of 90 meters. In these areas, individual TEM inversion was unable to identify the shallow soil layer within the first 10 meters. However, it did delineate the top and base of the basalt layer (the base of the basalt layer corresponds to the top of the Botucatu sandstone). In the Botafogo area, the top of the basalt layer was identified at a depth of 75 meters, and its base was approximately 660 meters deep. In the Andes area, these depths were 65 meters (top) and approximately 760 meters (base), respectively.

The joint inversion was able to resolve both the shallow (soil, sandstone, and top of the basalt layer) and deep layers (base of the basalt layer), covering the

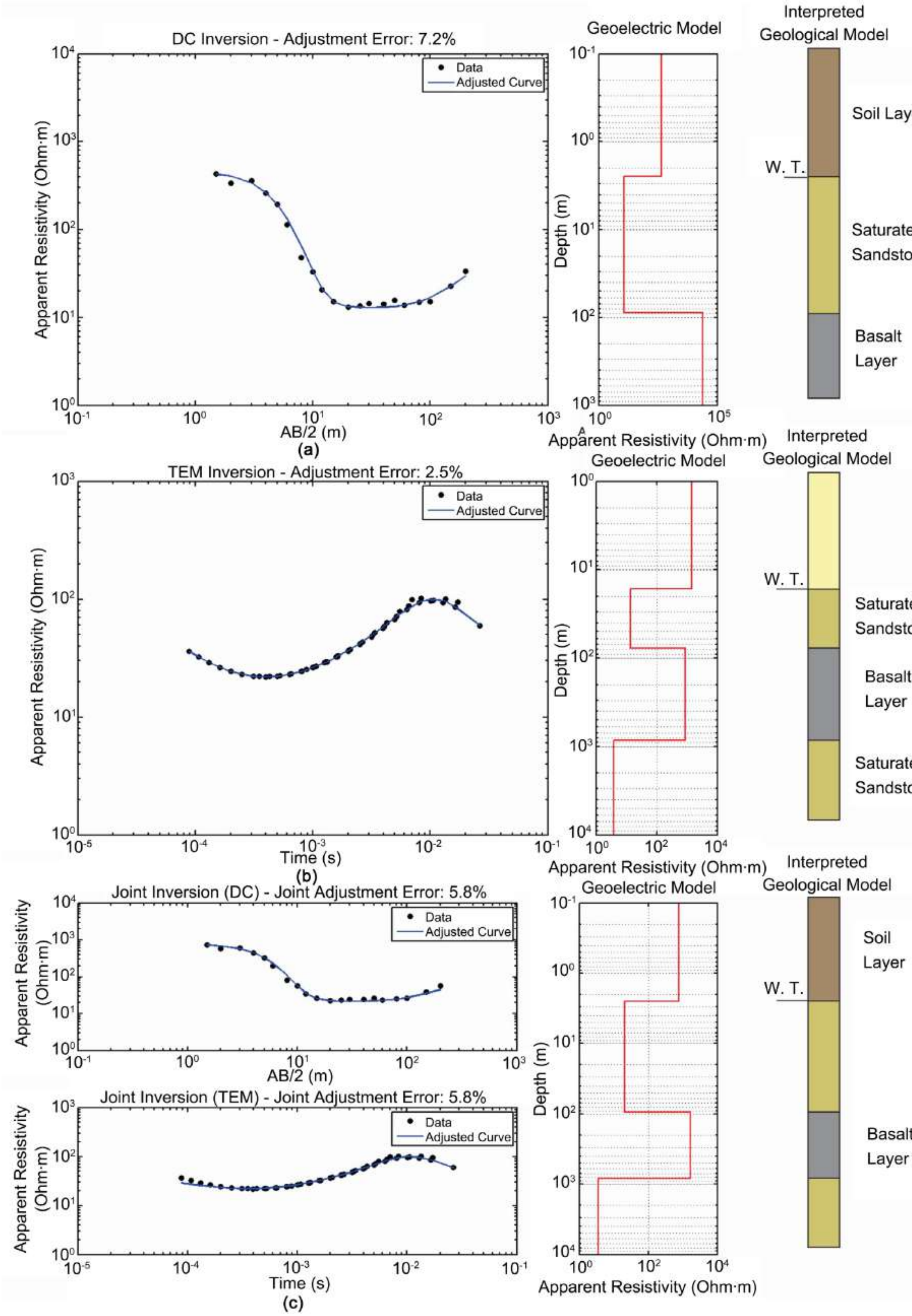

Figure 4. Inversion results for Andes district. In (a) the results with individual VES inversion, in (b) the results with TEM inversion and in (c) the results with the joint inversion.

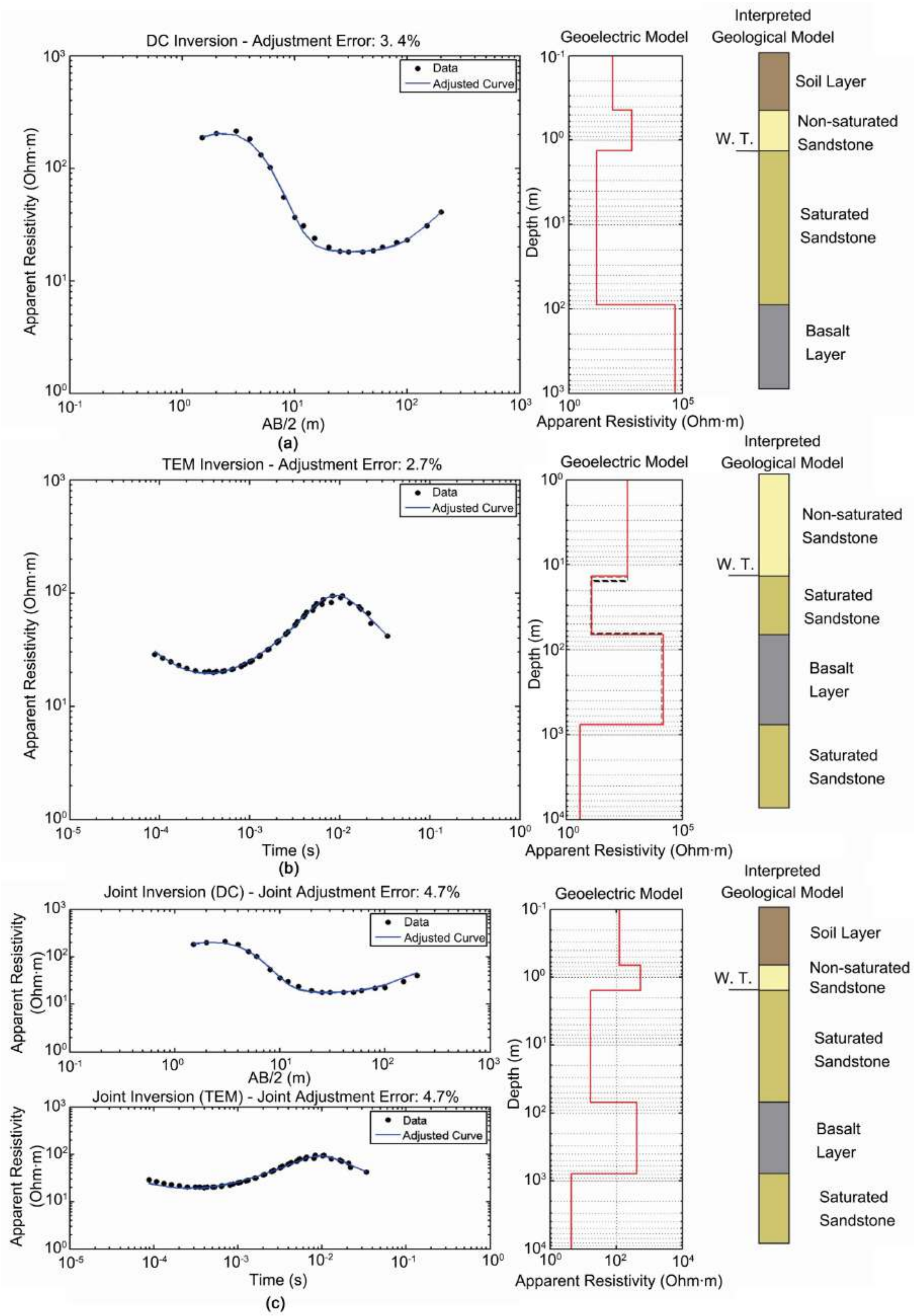

Figure 5. Inversion results for Andes district. In (a) the results with individual VES inversion, in (b) the results with TEM inversion and in (c) the results with the joint inversion.

entire depth interval investigated. The results from the joint inversion are highly consistent with the individual VES and TEM results, with layer depths that are compatible with those obtained through individual inversion methods.

6. Conclusions

The software has demonstrated its proficiency in simulating, modeling, and accurately inverting VES (Vertical Electrical Sounding) and TEM (Transient Electromagnetic) sounding data. Its versatility and accuracy make it an exemplary tool for both academic research and practical applications.

Specifically, Curupira v1.0 has addressed the limitations often encountered in TEM for shallow layers, while effectively extending the depth range beyond what traditional VES techniques can achieve. The synergy achieved through joint inversion of VES and TEM data offers significant advantages. This approach enhances our understanding of various geological parameters, such as lithology, water table depth, and the presence of conductive minerals or hydrogeological features. These insights are invaluable for applications like groundwater exploration, environmental assessments, and mineral prospecting. Additionally, the joint inversion technique plays a critical role in geohazard assessment, allowing for the prediction of risks like landslides, subsidence, and groundwater contamination. This helps in the development of more accurate hazard maps and informs evaluations of geological formation stability, thereby reinforcing public safety measures. The adaptability of joint inversion to diverse geological settings and research objectives further underscores its versatility, making it an indispensable tool for geoscientific investigations across a broad range of regions and applications.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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