Journal of Applied Geophysics 112 (2015) 157–174

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

# VES/TEM 1D joint inversion by using Controlled Random Search (CRS) algorithm

Cassiano Antonio Bortolozo [a,*], Jorge Luís Porsani [a], Fernando Acácio Monteiro dos Santos [b], Emerson Rodrigo Almeida [a]

[a] Universidade de São Paulo (USP), Instituto de Astronomia, Geofísica e Ciências Atmosféricas (IAG), Departamento de Geofísica, Rua do Matão, 1226, Butantã 05508-090, São Paulo, Brazil
[b] Instituto Don Luiz (IDL), Faculdade de Ciências, Universidade de Lisboa, 1749-016 Lisboa, Portugal

ARTICLE INFO

*Article history:*
Received 14 November 2013
Accepted 19 November 2014
Available online 28 November 2014

*Keywords:*
VES
TEM
1D joint inversion
Controlled Random Search (CRS)
Hydrogeology
Paraná Basin, Brazil

ABSTRACT

Electrical (DC) and Transient Electromagnetic (TEM) soundings are used in a great number of environmental, hydrological, and mining exploration studies. Usually, data interpretation is accomplished by individual 1D models resulting often in ambiguous models. This fact can be explained by the way as the two different methodologies sample the medium beneath surface. Vertical Electrical Sounding (VES) is good in marking resistive structures, while Transient Electromagnetic sounding (TEM) is very sensitive to conductive structures. Another difference is VES is better to detect shallow structures, while TEM soundings can reach deeper layers. A Matlab program for 1D joint inversion of VES and TEM soundings was developed aiming at exploring the best of both methods. The program uses CRS – Controlled Random Search – algorithm for both single and 1D joint inversions. Usually inversion programs use Marquadt type algorithms but for electrical and electromagnetic methods, these algorithms may find a local minimum or not converge. Initially, the algorithm was tested with synthetic data, and then it was used to invert experimental data from two places in Paraná sedimentary basin (Bebedouro and Pirassununga cities), both located in São Paulo State, Brazil. Geoelectric model obtained from VES and TEM data 1D joint inversion is similar to the real geological condition, and ambiguities were minimized. Results with synthetic and real data show that 1D VES/TEM joint inversion better recovers simulated models and shows a great potential in geological studies, especially in hydrogeological studies.


## 1. Introduction

Interpretation process ambiguities are always present in all kind of geophysical exploration. A way to reduce them consists in using different geophysical methods for the same problem. With a large and diverse database, ambiguities can be reduced, and the result becomes more trustful and close to reality. The challenge consists in the acquisition of different data sets related to subsurface physical proprieties from different geophysical methods. Data can be related to the same physical property or to some different properties. If the information is regarding the same physical property, data processing and interpretation are faster and simpler. Two methods exploring the same physical property in different manners are electrical and electromagnetic methods. Vertical Electrical Soundings (VES) and Transient Electromagnetic Soundings (TEM) explore vertical and lateral variations of resistivity in the underground. It is possible to make a simple approximation of underground for both methods in which subsurface has horizontal and isotropic layers with associated resistivity and thickness transforming these methods in ideal ones for a combined use.

Electrical methods (DC) are widely used in geophysics. The applications of these methods range from geotechnical, through mining, hydrogeological and environmental studies. They are widely used due its relatively low cost, velocity and survey reliability. Electromagnetic surveys are also widespread in mineral exploration, geotechnical engineering, and hydrogeology. Electromagnetic surveys can be divided into electromagnetic methods in frequency (FDEM), and time (TEM) domains. TEM has great potential in many applications, mainly in hydrogeological studies, and similar to geophysical methods, it has advantages and limitations. In Brazil, TEM method use is now increasing and some works are done in hydrogeological studies (Bortolozo et al., 2014; Carrasquila and Ulugergerli, 2006; Porsani et al., 2012a,b).

Time-Domain Electromagnetic method can accurately mark conductive structures and it has a great depth of investigation, in relation to the size of the loop used. In turn, Vertical Electrical Sounding method defines resistive structures very well, and can detect the most superficial subsoil layers. In this way, VES and TEM methods complement each other. However, the difference between how it obtains apparent resistivity curves makes the joint analyses complicated. In VES case, the

* Corresponding author at: Avenida Escola Politécnica, 2200, Ap. 42G - Bairro Rio Pequeno - São Paulo - SP CEP: 05350-000. Phone: +55 11 30912790 Cel: +55 11 976826063.
*E-mail addresses:* cassianoab@gmail.com, cassianoab@gmail.com (C.A. Bortolozo), porsani@iag.usp.br (J.L. Porsani), fasantos@fc.ul.pt (F.A.M. Santos), emerson1983era@gmail.com (E.R. Almeida).

http://dx.doi.org/10.1016/j.jappgeo.2014.11.014
0926-9851/

apparent resistivity curve is measure varying the electrode opening. In TEM sounding, apparent resistivity curve is measure as a function of medium time response. Therefore, apparent resistivity curve is in function of meters (AB spacing) in VES, and in TEM sounding, the apparent resistivity is in function of seconds. Then, analyses must be done by an inversion algorithm in order to deal with both databases, simultaneously.

With the aim of analyzing TEM and VES data more accurately and reliably the two-database joint inversion is necessary. In such case, it simultaneously does TEM and VES data inversion. Vozoff and Jupp (1975) assigned pioneering works related to the joint inversion of magnetotelluric data (MT) and Vertical Electrical Sounding (VES). In that article, authors showed the advantages of joint inversion, demonstrating how this process is synergistic, i.e., the final result is more than the sum of individual results of both methods. In this line of research, some studies have discussed the advantages of DC and TEM data joint inversion (Meju, 1996; Raiche et al., 1985; Yang and Tong, 1999), all showing the advantages of two-methodology joint use. Goldman et al. (1994) and Albouy et al. (2001) have applied the joint inversion of those methods in hydrogeological studies. Examples of application to potential risk of slopes are in Schmutz et al. (2000) and Schmutz et al. (2009).

Most of times, the inversion programs use a Marquadt type algorithm, which employs derivatives to find the global minimum. The problem in using this kind of algorithm for electric and electromagnetic methods is these methods have many local minimums, and the process may stop in a local minimum, leading to an erroneous model. In Monteiro Santos and El-Kaliouby's (2010) work, the authors compared derivative methods with global search methods for 1D joint inversion of VES/TEM, and they established the best ones for this case were global search ones.

A global search algorithm tries to find the objective function global minimum by searching the solution normally by a random search. The simplest approach would be to test all possible models but this would be impractical, even with the few amount of parameters normally used in 1D inversions. To overcome this problem, the search uses in many different ways random elements to map and find the global minimum of the objective function. Methods that incorporate random models inside algorithm are called Monte-Carlo methods (Mosegaard and Sambridge, 2002).

By using random models, it is possible to search objective function minimums faster than using systematic research (Mosegaard and Tarantola, 1995). However, simply testing a large number of random models without any control will be computationally expensive. To speed up the search, different techniques are developed to narrow the random search, it is worth to mention, among them: Simulated Annealing algorithm (Sen and Stoffa, 1991), neighborhood algorithm (Sambridge, 1999a,b), and genetic algorithms (Goldberg, 1989). CRS – Controlled Random Search – algorithm developed by Price (1977) is an algorithm that uses random models in a controlled form to be more efficient than only search random models but, also, robust enough to not fall in a local minimum. CRS was designed for thoroughness of search rather than for speed of convergence (Price, 1977), so it is not as fast as most of derivative methods but has at most a minimum chance to stop in a local minimum.

Since its development, CRS algorithm is worldly used in different kinds of applications. In Kim et al. (2005) work, they used CRS algorithm to determining the near-optimal settings of welding process parameters. The algorithm was also used for optimizing regression models (Křivý and Tvrdík, 1995; Křivý et al., 2000). In Merad et al. (2006), the authors formulated an optimization problem for designing nonuniformly spaced linear antenna arrays by using CRS algorithm. In geophysics, the use of CRS algorithm was especially in seismic, magnetic and magnetotelluric problems. Červ et al. (2007) used CRS algorithm to invert magnetotelluric data, obtaining good results. Smith and Ferguson (2000) demonstrated the benefits of CRS use when working with seismic refraction data, especially when focused on specific target investigation, CRS method proved highly effective at quantifying the statistics of the models. Silva and Hohmann (1983) used CRS for magnetic interpretation, concluding the algorithm is very robust, and, for the magnetic case, it can generate great results especially when geologic and geophysical information is available. All works involving the algorithm demonstrate the random search algorithms perform very well and are robust as they give great parameter determination for ill-structured global optimization problems.

In this article, we present a new approach to VES and TEM sounding 1D joint inversion the problem by using CRS algorithm, by the development and implementation of a program and the use of this methodology in southeastern Brazil. Joint inversion results are compared with results of individual inversions aiming at analyzing the advantage of 1D joint inversion. Therefore, this research may be of interest mainly for its application in hydrogeological studies, with emphasis on mapping fractured and sedimentary aquifers in tropical soils, for instance, at Paraná sedimentary basin.

## 2. Numerical modeling and inversion algorithm

The first step in the development of an inversion algorithm is the computation of the forward problem, which consists in our case in VES/TEM sounding numerical modeling. For VES, the code was developed based on Johansen (1975) by using linear filters to obtain the apparent resistivity. For TEM sounding (central loop), the program was developed using the filters developed by Christensen (1990) in the same form as Nielsen and Baumgartner (2006). CRS – Controlled Random Search – algorithm, developed by Price (1977) for global optimization was used in inversion. This algorithm is very adequate for our problem. The algorithm is very robust and a global inversion algorithm is the most indicate for VES/TEM data 1D joint inversion, as demonstrated by Monteiro Santos and El-Kaliouby (2010).

### *2.1. VES modeling*

The method of linear filtering applied to electrical methods was developed by Ghosh (1971a,b). This method allows calculating the apparent resistivity with little computational cost, essential for a useful code. This method is consisting in solving the resistivity function integral by a convolution. The resistivity transform function is convolved with a set of previously calculated filters, and the result of this convolution is the apparent resistivity. Johansen (1975) improves the technique by using a longer set of filters, and it greatly increased the calculation accuracy. Thus, Johansen's formulation was used in this work.

Then, the apparent resistivity at the sampling points ($x_i = i\Delta x$) is given by:

$$\rho_a(i\Delta x) \sim \sum_{j=j_{min}}^{j_{max}} T((i-j)\Delta x + S)C(j\Delta x - S) \tag{1}$$

where $T$ is the resistivity transform function; and $C$ is the filter coefficients. In such a case, $j_{min}$ and $j_{max}$ are chosen, so that the filter coefficients with smaller or larger ratios may be neglected. $S$ is a displacement factor calculated as demonstrated in Koefoed (1972) and Johansen (1975).

Resistivity transform for a stratified medium (Fig. 1a) can be calculated recursively (Koefoed, 1970). For a geoelectric layer above basement, the transform can be computed by using exponential formulation as:

$$T_{N-1}(\lambda) = \rho_{N-1}\frac{1-k_{N-1}e^{-2h_{N-1}\lambda}}{1+k_{N-1}e^{-2h_{N-1}\lambda}} \tag{2}$$

$$k_{N-1} = \frac{(\rho_{N-1}-\rho_N)}{(\rho_{N-1}+\rho_N)}. \tag{3}$$