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JOINT USE OF SHALLOW VES AND LARGE LOOP TEM DATA TO INTERPRET TEM SOUNDINGS

Abstract. An appropriate definition of apparent resistivity, faithfully reflecting the variations in the electrical behaviour of subsurface layers, is crucial to the interpretation of transient or multifrequency EM sounding data using controlled sources. For a number of time-domain EM (TEM) methods, the practice has been to use asymptotic expressions for the induced voltage to derive apparent resistivity vs. time curves. The drawback with this approach is that the apparent resistivity curves neither have much resemblance with the subsurface resistivity variations nor do they reflect the number of layers present. In this paper an all time apparent resistivity for large loop TEM systems is defined combining shallow VES information such that the subsurface resistivity variations and the number of layers are reflected well. After presenting curves for some theoretical models, the efficacy of the proposed definition is examined through published field examples. It is shown that the definition presented in this paper is useful in selecting a better initial guess model that leads to more realistic predictions of the subsurface structures. The approach presented in this paper is expected to be useful in the routine interpretation of TEM sounding curves using large loop transmitters.

INTRODUCTION

An appropriate definition of apparent resistivity, faithfully reflecting the variations in the electrical behaviour of the subsurface layers, is crucial to the interpretation of EM sounding data. While for the MT soundings, the apparent resistivity is well defined as a function of frequency or time, in the case of controlled source methods it is relatively more difficult to propose a satisfactory definition of the apparent resistivity. For such methods, it is a common practice to present the frequency (or time) domain sounding curves as normalized impedance values (Keller and Frischknecht, 1966; Wait, 1955; etc). These impedance values, however, fail to yield any diagnostic clue about the number of subsurface layers or about their resistivity variations.

For some of the time-domain electromagnetic (TEM) methods, employing grounded cable sources, attempts have been made to use an asymptotic expression for the induced voltage to derive early time and late time apparent resistivity vs. time curves (Ibrahim, 1982; Kaufman and Keller, 1983; Stoyer and Strack, 1984; etc.). The drawback with this definition once again is that the resulting curves do not bear much resemblance to the subsurface resistivity variations. Also, the number of layers cannot be deduced by studying the features of these curves. In order to obviate such limitations, Sheng (1986) proposed a method to calculate an all time apparent resistivity curve. However, the proposed scheme fails for certain time ranges even in the case of some simple two-layer or three-layer earth models. More recently, using the expression for magnetic field rather than its derivative, Karlik and Štrack (1990) have been able to present a more realistic definition of the all time apparent resistivity curve for a large grounded dipole system.

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In this paper a technique is proposed to compute apparent resistivity vs. time curves for a rectangular loop transmitter by employing the additional information from the shallow VES data. A number of large loop TEM systems like EM-37, EM-47, EM-42 (all trade names used by Geonics, Canada) and SIROTEM (Busselli and O'Neill, 1977) that employ large loop transmitters are now available commercially. Such systems are frequently employed for solving problems relating to a number of geophysical applications, such as mapping of subsurface contaminated and polluted zones, foundation engineering, exploration for groundwater and minerals, mapping of freshwater-saline-water interface and waste-disposal etc.

The efficacy of the proposed scheme is established by presenting theoretical curves for some standard layered earth models. A comparison of the proposed definition with the currently employed definitions based on the late time asymptote (Kaufman and Keller, 1983) and a graphical approach (Rabinovich, 1973 and Goldman, 1988) is also presented to demonstrate the advantages of the proposed scheme. A few examples from published case histories (Goldman, 1988) have been selected for the purpose of illustrations.

THEORY

The theory for computing EM sounding curves in the frequency-domain for a large rectangular loop is given by Poddar (1983). Using a cosine transformation, Anderson (1985) developed a numerical scheme to obtain corresponding results in the time domain. He then used a series approximation following the approach proposed by Pracser (1986) to define the apparent resistivity. It is shown by Anderson (1985) that the apparent resistivity computed following Pracser's approach is more accurate than the values computed through the late time asymptotes. Thus Pracser's approach is definitely a better way of computing transient apparent resistivity curves for large loop TEM systems. However, we find (and show later) that even the series approximation proposed by Pracser (1986) does not yield accurate apparent resistivity values at early times. Therefore, in order to overcome this limitation, we propose that the early time values be obtained separately, utilizing the information from shallow vertical electrical sounding (VES) measurements. It is shown that a fusion of the shallow VES information with apparent resistivity values obtained by Pracser's approach greatly improves the quality of the apparent resistivity curves.

First, a brief description of the theory to compute the apparent resistivity for a large loop, following Pracser's approach as well as the late time asymptote method, is presented below.

The H_z field component inside or outside a rectangular loop (Fig. 1) at the point (X_0, Y_0) can be written as (Anderson, 1985)

$$H_z(\omega) = \frac{I}{2\pi}(H_{L1}+H_{L2}+H_{L3}+H_{L4}), \quad (1)$$

where the current I.exp (iωt) is flowing in the loop. With the help of the Fourier cosine transform, the time derivative of the H_z component in the time domain $H_z'(t)$ can be expressed as (Kaufman and Keller, 1983, P. 360)

$$H_z'(t) = \frac{2C}{\pi}\int_0^{\infty} R_e\left[\frac{H_z(\omega)}{H_{zp}}\right].\cos\omega t.d\omega, \quad (2)$$

where both sides of eqn. (2) are normalised by the primary field H_{zp} (Poddar, 1982) such that the constant C in eqn. (2) is a product of H_{zp} and any arbitrary receiver moment M (=n A; n being the number of turns and A the area of the source loop).

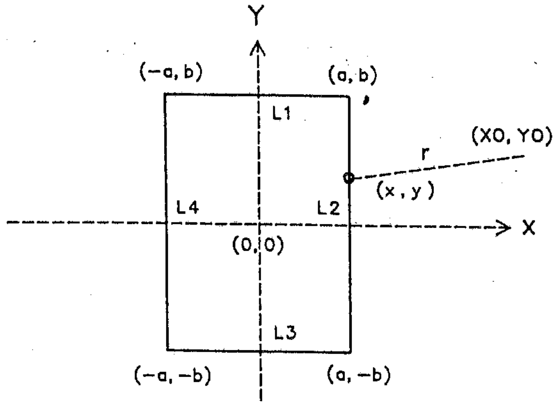

Fig. 1 — Coordinate system and the geometry of the rectangular loop at the earth's surface.

Apparent resistivity computation using Pracser's approach

Following Pracser (1986) the apparent resistivity is computed from the voltage function $(=\frac{\partial Hz}{\partial t})$ that can be expanded in the following series for a rectangular loop:

$$V(t)=C_0 \sum_{k=1}^{\infty} C_k \alpha^{2k+1} \{ \sum_{j=0}^{k-1} \frac{\binom{k-1}{j}}{2(k-j)+1} [(a-X_0)^{2(k-j)-1}-(-a-X_0)^{2(k-j)-1}] * [(Y_0-b)^{2j+1}-(Y_0+b)^{2j+1}] + \sum_{j=0}^{k-1} \frac{\binom{k-1}{j}}{2(k-j)+1} [(b-Y_0)^{2(k-j)-1}-(-b-Y_0)^{2(k-j)-1}] * [(X_0-a)^{2j+1}-(X_0+a)^{2j+1}]\} , \quad (3)$$

where $C_0=\mu_0 M / (4\pi^{3/2} t)$,

$$V(t)= \frac{\partial H_z(t)}{\partial t} ,$$

$$C_k=(-1)^{k+1} [2-b / (2k+3)] / k! ,$$

$$\mu_0=4\pi.10^{-7}$$

and

$$\alpha=[\sigma\mu_0 / 4t]^{1/2} .$$

The apparent resistivity ϱ_a^P (superscript P is used to denote Pracser's approach), at any time t, can be computed by solving the following nonlinear equation for α:

$$A_\alpha=\frac{1}{t} \sum_{k=1}^{\infty} C_k \alpha^{2k+1} (F_k)-V(t)=0 , \quad (4)$$

where A_α is the function of α to be solved and F_k are the terms within "{.....}" in eqn. (3). It may be noted that while equating eqn. (2) with eqn. (3) the receiver-moment gets cancelled on both sides, assuming that in eqn. (2) C contains the receiver-moment. In terms of computation, only a few terms of the series (generally <10) are required to solve for α. For a real root of α $(=\alpha_t)$ at any $t^* > 0$, the apparent resistivity $\varrho_a^P(t^*)$ can be computed by

$$\varrho_a^P(t^*) = \frac{\mu_0}{(4t^*.\alpha_t^2)} \; . \tag{5}$$

Late time asymptotic approximation

The late time asymptotic values ϱ_a^{LT} (LT denotes late time) can be computed if only the first term in eqn. (4) is considered (Anderson, 1985). In that case a trivial solution for ϱ_a^{LT} could be written as

$$\varrho_a^{LT} = \left[\frac{1.6ab\mu_0}{(t \mid V(t) \mid)}\right]^{2/3} . \; \frac{10^{-7}}{t} \; . \tag{6}$$

We find that the ϱ_a^{LT} curves can yield realistic values of the apparent resistivities even at early times for highly resistive ($\varrho_1 > 1000\ \Omega.m$) over-burden situations. As the earth-structure becomes more conductive, higher order terms in eqn. (4) are required to be computed.

RESULTS

Fusion of the shallow VES and $\varrho_a^P(t)$ curves

It is found that except at very small times (i.e. at shallow depths) the apparent resistivity values using $\varrho_a^P(t)$ reflect the subsurface resistivity variations and the number of layers reasonably well. To get an idea about the resistivity at early times, it is proposed that the information from vertical electric soundings (VES) using small electrode spacings be utilized to supplement the apparent resistivity curve obtained by eqn. (5). While doing so, the resistivity values corresponding to that for the VES, i.e. ϱ_a^S (where the superscript is used for the particular array employed in the field, for example, S for Schlumberger), as well as that for TEM (i.e. ϱ_a^P) should be plotted using the ordinate-axis with the same log scale. The log scale corresponding to the abscissa (representing electrode separations for the ϱ_a^S curve and time for the ϱ_a^P curve) should be adjusted somewhat for ϱ_a^S such that the initial patterns reflected by the two resistivity curves (i.e., ϱ_a^P and ϱ_a^S) coincide. The fusion of the two apparent resistivity sounding curves is then complete to yield reasonably accurate all time apparent resistivity curves designated as $\varrho_a^{AT}(t)$.

Illustrations to support the above approach are presented in Fig. 2 (a and b). The models considered in these figures are typical of petroliferous Mesozoic sediments (20 Ω.m layer) that occur beneath a basaltic cover (Deccan Traps, 200 Ω.m) in the western part of India. In the first model (Fig. 2a) we have also included a 30-m-thick weathered layer on top (resistivity 50 Ω.m). The shallow depth VES information (ϱ_a^S), providing supplementary information at early times, is plotted in circles. This indicates the initial value of the apparent resistivity as 50 Ω.m. The ϱ_a^S curve then shows a high that corresponds well with the resistivity of the Traps. This value also matches (and almost merges) with the $\varrho_a^P(t)$ values (shown by the solid curve). The two curves (i.e., ϱ_a^S and $\varrho_a^P(t)$ are then merged to form a single all time apparent resistivity curve $\varrho_a^{AT}(t)$, which is shown by black circles. In the absence of the top weathered layer (Fig. 2b), the initial values ϱ_a^S correspond to the resistivity of the Traps. Subsequently the low resistivity for the sediments and the high resistivity for the basement are observed in the $\varrho_a^P(t)$ curves. The fused curve in black circles once again reflects the subsurface resistivity variations reasonably well. We have also compared the apparent resistivity curve (presented

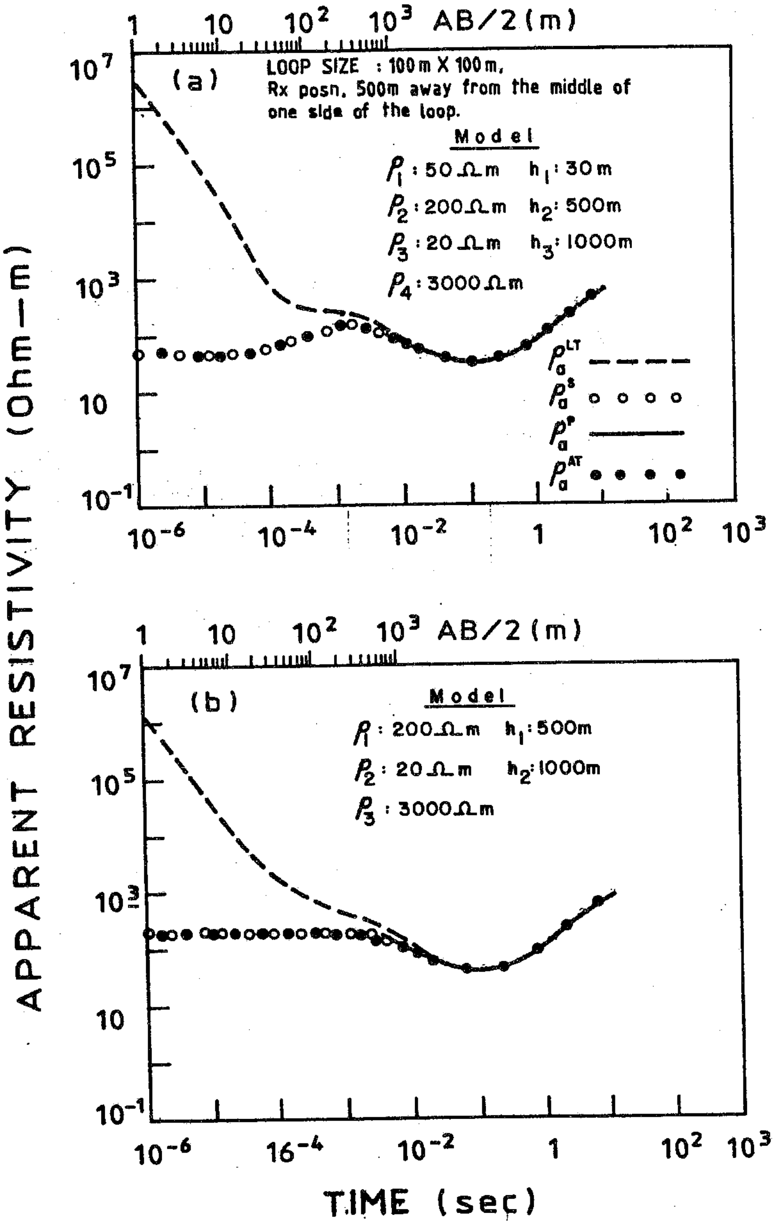

Fig. 2 — All time (ϱ_a^{AT}) and late-time (ϱ_a^{LT}) apparent resistivity curve considering step pulse excitation for a typical model of sub-trappean sediments: a) with a weathered layer on top; b) without the weathered overburden.

in Figs. 2a and 2b) with those obtained using the late time asymptotic approximations ϱ_a^{LT} *(t)* (shown in dashed curves). It may be seen that the discrepancy between the two curves (i.e., the all time ϱ_a^{AT}, and the late time ϱ_a^{LT} curves) is very large at early times. Also, the apparent resistivities reflected by the ϱ_a^{LT} *(t)* curves are unrealistic for initial three log cycles in time. The importance of ϱ_a^{AT} *(t)* curves lies in the fact that they represent subsurface resistivity changes more realistically. Thus these curves enable the interpreter to choose an initial model close to the actual model. This is vital because most of the inversion algorithms are based on generalized linear inversion, which requires the initial guess model to be in the vicinity of the actual model. This is demonstrated in the field examples shown below.

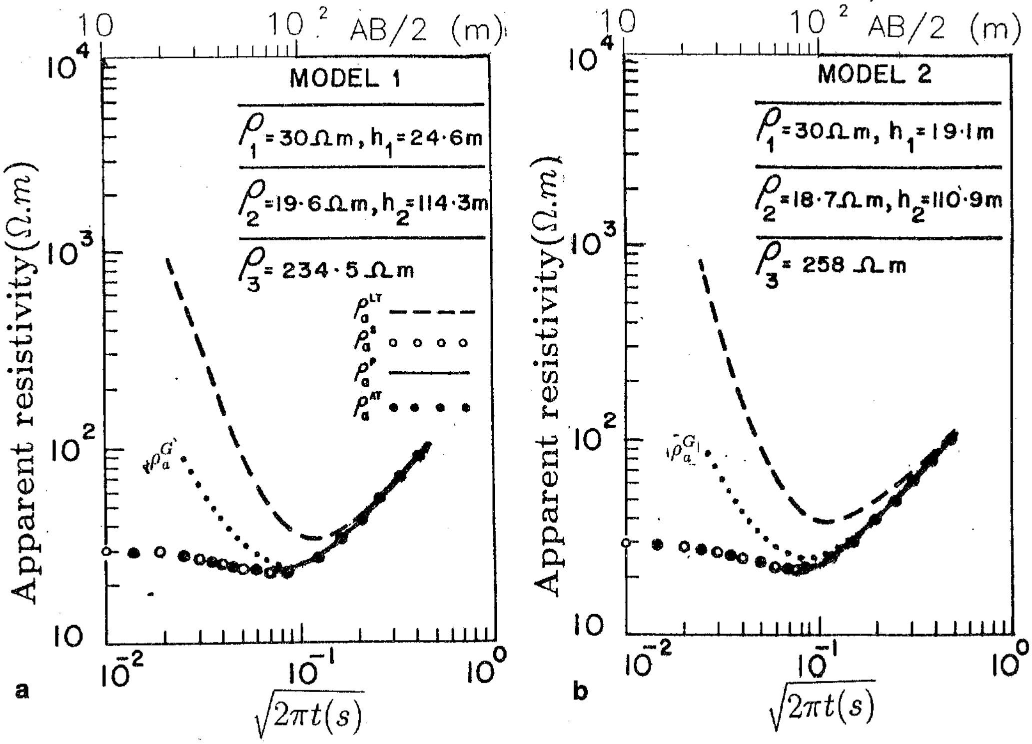

Fig. 3 — Comparison of ϱ_a^{AT} curve with the ϱ_a^G and ϱ_a^{LT} curves: a) for Model 1 (Gurim area Station 3) presented in Fig. 3a of Goldman (1988); b) for Model 2 (Gurim area Station 3, Negev Desert, Israel) presented in Fig. 3b of Goldman (1988).

Field examples

To show the practical usefulness of the proposed approach, the field TEM results published by Goldman (1988) were compared with those obtained by using the present approach. Goldman (1988) used a graphical construction of a multi-layered apparent resistivity curve employing a combination of two-layered curves originally due to Rabinovich (1973). Employing this approach, Goldman presented curves from the Gurim and Mishor Rotem areas of the Negev Desert, Israel (Figs. 3a and b, 4a and b, and 5a and b in his paper). We have plotted the ϱ_a^{AT} values (Figs. 3, 4 and 5 in this paper) computed by the present approach on the figures obtained by Goldman (1988) to compare the resistivity structures displayed by the two approaches. The late time values ϱ_a^{LT}, and the shallow depth resistivity values ϱ_a^S (up to half-electrode spacing of 100 m using the Schlumberger array) are also plotted. It can be seen that in all cases the apparent resistivity values obtained by Goldman (1988) ϱ_a^G (superscript G for Goldman) as well as ϱ_a^{LT} are very high in comparison to the actual values. The apparent resistivity curve ϱ_a^{AT} proposed in the present paper shows a much better resistivity structure compared to ϱ_a^G or ϱ_a^{LT} curves. At early times, in all cases, the ϱ_a^{AT} values based on ϱ_a^S values are closer to the top-layer resistivity value, which is not reflected in the ϱ_a^G values.

Using the initial models presented by Goldman (Tables 1 and 2 in his paper) we have tried to invert the data for the models shown in Figs 4 (b) and 5 (b) of Goldman's paper. The results are presented in Figs. 6 and 7. From Fig. 6 it is apparent that the inversions using voltage V (t) values or ϱ_a^{AT} values yield results that are within the acceptable limits (<10 percent of the values presented by Goldman, 1988). However, the resistivity of the second layer (ϱ_2) is not resolved well if ϱ_a^{LT} values are used. On the other hand the inversion of ϱ_a^{LT}, ϱ_a^{AT} and voltage values yield the exact model for the example presented in Fig. 7. This is due to the fact that a conductive sandwiched layer makes an easy target for EM methods in general.

If the top layer resistivity is not known and the initial guess model is chosen on the basis

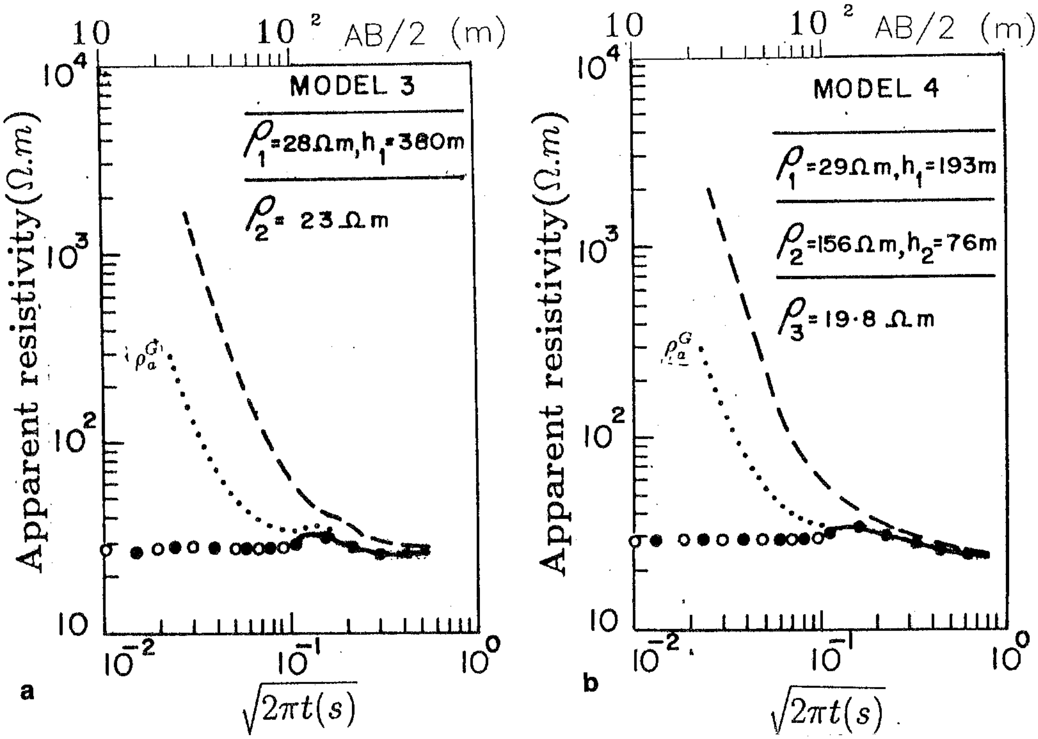

Fig. 4 — Comparison of ϱ_a^{AT} curve with the ϱ_a^{G} and ϱ_a^{LT} curves: a) for Model 3 (Mishor Rotem area Station 1, Negev Desert, Israel) presented in Fig. 4a of Goldman (1988); b) for Model 4 (Mishor Rotem area Station 1, Negev Desert, Israel) presented in Fig. 4b of Goldman (1988).

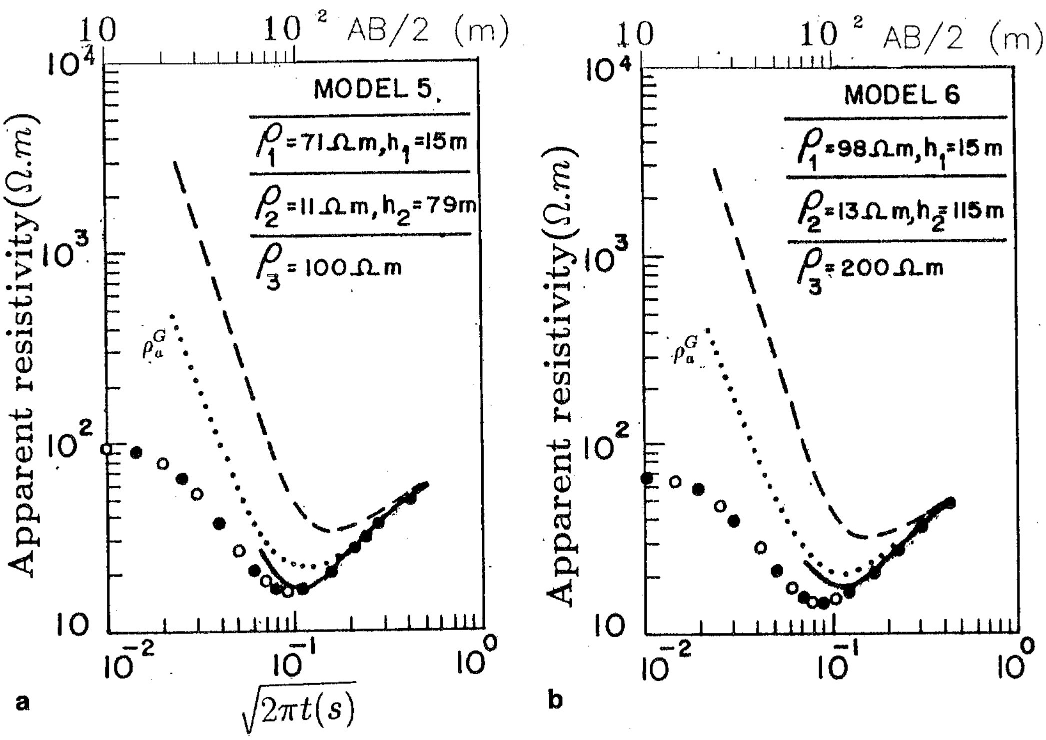

Fig. 5 — Comparison of ϱ_a^{AT} curve with the ϱ_a^{G} and ϱ_a^{LT} curves: a) for Model 5 (Gurim area Station 2, Negev Desert, Israel) presented in Fig. 5a of Goldman (1988); b) for Model (Gurim area Station 2, Negev Desert, Israel) presented in Fig. 5b of Goldman (1988).

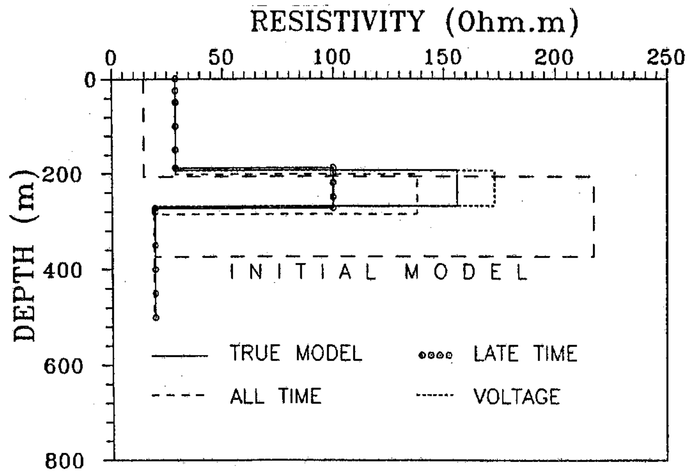

Fig. 6 — Inversion results for the Model 4 (Mishor Rotem (Station 1), Negev Desert, Israel) for the initial guess model considered by Goldman (1988, Table 1).

of ϱ_a^G or ϱ_a^{LT} curves, one is likely to guess a higher value of the top layer resistivity ϱ_1. Possible errors due to higher ϱ_1 values in the initial model are shown in Figs. 8 and 9. For the Mishor Rotem area (Station 1), we can see (Fig. 8) that higher estimates of the ϱ_1 and h_2 values are obtained by inverting the ϱ_a^{LT} curve. Inversion of the voltage data yields acceptable values for ϱ_1 but higher values of the parameter h_2. Since the inversion of ϱ_a^{AT} involves realistic estimates of ϱ_1 values (as obtained from shallow VES curves), we obtain a model correct to within acceptable limits. In the case of the Gurim Area (Station 2) (Fig. 9) inversion of both ϱ_a^{LT} as well as voltage values yields higher estimates of ϱ_1 values. However, in comparison to the large value of 985 Ω.*m* obtained from the ϱ_a^{LT} curve, the voltage curve yields the value 302 Ω.*m*, which is much closer to the true values of 98 Ω.*m*. Other parameters are resolved well by all the curves due to the conductive nature of the sandwiched layer.

Advantage of all time apparent resistivity

It may be seen from Figs. 3, 4 and 5 that the apparent resitivity curves obtained by the approach based on the Rabinovich (1973) - Goldman (1988) method (ϱ_a^G curves) and those

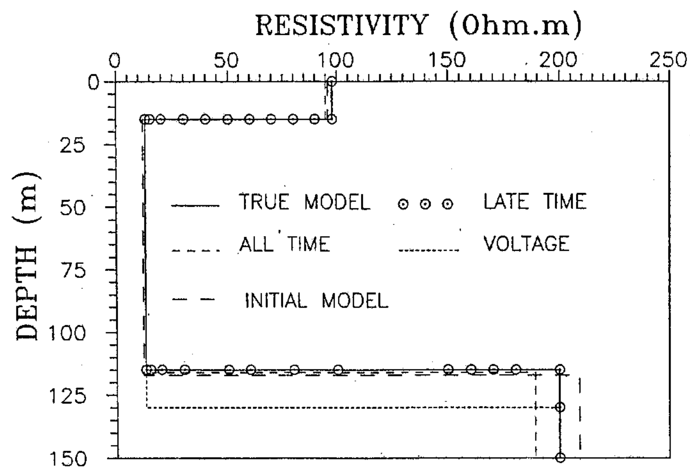

Fig. 7 — Inversion results for the Model 6 (Gurim area (Station 2), Negev Desert, Israel) for the initial guess model considered by Goldman (1988, Table 2).

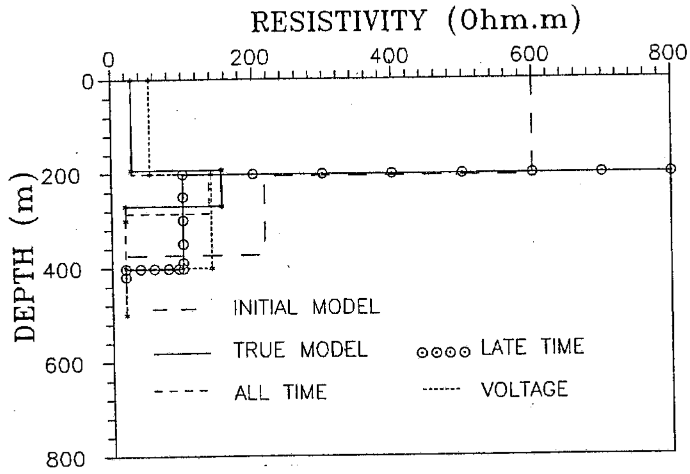

Fig. 8 — Inversion results for the Model 4 (Mishor Rotem (Station 1), Negev Desert, Israel) considering $\varrho_1 = 600$ $\Omega.m$ in the initial guess model.

obtained by employing the late time asymptotic values (ϱ_a^{LT} curves) yield unrealistically high values of the apparent resistivity at early times. Choosing an initial model from these curves will be difficult, as the top layer resistivity will be assumed much higher than its actual value. This then is likely to lead to inaccurate results after inversion. Goldman (1988) could overcome this problem by using a number of starting parameter vectors randomly distributed within a feasible parameter range. However, in his approach the forward algorithm is semi-empirical and cannot be applied for an abritrary multi-layered geoelectric model.

The present approach is advantageous in that it incorporates accurate computation of any arbitrary multi-layered earth model. Once the ϱ_a^{AT} curve is obtained by including the shallow depth VES (ϱ_a^S) information, selecting an initial model is rather straightforward. Selection of a reasonable initial model is vital in arriving at a realistic final model. This is illustrated through Figs. 8 and 9, where we have selected an initial model with top layers of high resistivity as reflected by the ϱ_a^G and ϱ_a^{LT} curves. From these figures it becomes clear that if high resistivity values at early times are considered to select an initial model, erroneous results are obtained after inversion. Therefore it is important to select a realistic initial model that is not based

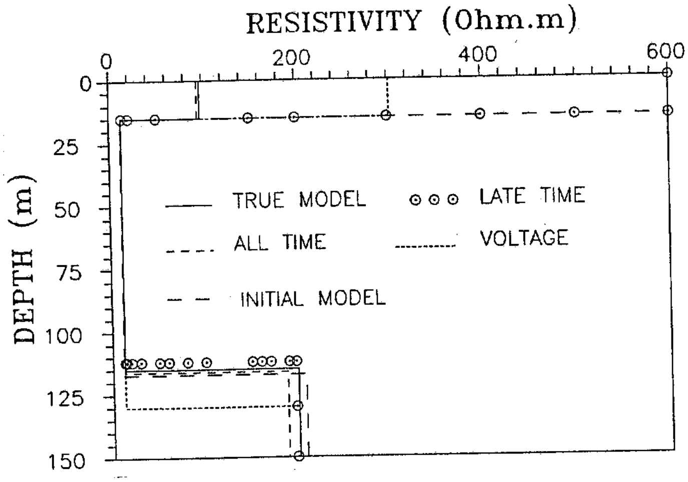

Fig. 9 — Inversion results for the Model 6, (Gurim area (Station 2), Negev Desert, Israel) considering $\varrho_1 = 1000$ $\Omega.m$ in the initial guess model.

on the very high early time value of the apparent resistivity obtained using ϱ_a^G or ϱ_a^{LT} values. This can be achieved by fusing the shallow VES information and the $\varrho_a^P(t)$ curve leading to a realistic all time apparent resistivity curve.

Limitations of the proposed approach

Though the proposed scheme works well for the theoretical and field examples presented in the paper, and is expected to work well in most situations, it is felt necessary to caution that in some cases the approach may not be fully successful. These are mentioned below:

i. The proposed fusion of TEM and VES curves essentially deals with two different classes of data. While the TEM data is temporal, the VES data is spatial. Only qualitatively can the information based on smaller (VES) spacings be considered equivalent to the early time information. The two data sets, in fact, are reciprocally non-homogeneous kinds of data and the proposed fusion is rather empirical in nature.

ii. The proposed technique fuses two data sets obtained over a stratified earth model. If the real-life earth model consists of non-horizontal structures or confined heterogeneities, the proposed method will lead to erroneous results.

CONCLUSIONS

An approach is presented to construct all time apparent resistivity curves fusing the definition proposed by Pracser (1986) and the shallow VES information. The all time apparent resistivity curve thus obtained can be advantageously employed to select proper initial models that yield realistic inversion results. Unlike the approach suggested by Goldman (1988), the present approach is valid for any arbitrary multilayered earth structure. Further it is found that once an appropriate initial guess model is obtained, inversion of voltage data yields more accurate inversion results. In general, the inversion of ϱ_a^{LT} should be avoided for less resistive ($\varrho_1 < 1000\ \Omega.m$) overburden situations.

The present approach is also expected to provide better information on the subsurface electrical structure, as the information from the VES data and from the TEM data can be jointly inverted to arrive at a more accurate interpretation (Sandberg, 1993).

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