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Applicability Study of Coincident Loop Transient EM Soundings

Petros Karmis [1], Taxiarchis Papadopoulos [2], Ioannis F. Louis [2]

[1] Institute of Geology and Mineral Exploration, Geophysics Department,
75 Mesogion 115 27 Athens Greece

[2] Geophysics - Geothermy Division, Geology Department, University of Athens

Abstract: *Model studies have been undertaken in order to investigate the applicability of Transient EM soundings using the coincident loop configuration. The models included 2 layer and 3 layer cases, studying the effect of varying the thickness of the first layer in the 2 layer case and the mid layer in the 3 layer case, with conductivity contrasts ranging from zero to one hundred. The effect of the loop size on resolution of the first layer and the detectability of the intermediate conductive and resistive target layers were also examined. Finally the models included 4 and 5 layer cases to assess the ability to detect resistive and conductive targets in complex structures and point out the advantages of the TEM method comparing to the Electrical DC method.*

INTRODUCTION

The Transient EM sounding technique is successfully applied to various sectors of areas of geo-exploration. It has been first applied to mineral and geothermal exploration and it was successfully introduced to hydrogeological, engineering geology and environmental studies.

The scope of this paper is to study the problem of resolving a horizontally layered earth sequence, with respect to the following issues: a) The detectability of the top layer of variable conductivity and thickness in the 2 layer case, b) the effect of the loop size in resolving the thickness of the top layer, c) the detectability of the conductive and resistive of intermediate layer, of variable conductivity and thickness in the 3 layer case and d) the capability to resolve multilayered earth structure and relative assessment of the TEM advantages compared to the Electrical DC method.

The method uses a rectangular loop as its source, energized by a constant amplitude current periodically switched on and off. The current waveform is square and bipolar and the off-time varies from 30 to 180 ms. The off time is equal to on time and the turn off is a linear ramp in the range of 30 to 300 ì s, depending on the loop size and current amplitude.

Most transient EM units measure the mutual impedance at time t, $Z(t) = V(t)/I$ between the transmitter and receiver loops. This is effectively the voltage V induced in the loop, normalized by the current I and it is related to the secondary magnetic field induced in the earth by the decaying current system via the following relation: $V = \mu_0 m \frac{dB_z}{dt}$,
where m_0 is 4ð*10^{-7} , m is the turns-area product of the loop and B_z the vertical component of the secondary magnetic field.

The forward model calculations are conducted assuming a step function current waveform (Sirotem), the coincident loop configuration and taking into account the turn off time. The main algorithm of the forward program, including the inverse Laplace transform and Hankel transform calculation routines is based on Sandberg (1990), and Anderson (1979) work after modifications including the specific instrument output characteristics, configuration mode and the derivation of ramp corrected resistivity values.

LAYERED EARTH IMPEDANCE CALCULATION

The problem of calculating the Time domain EM response of layered media has been addressed in a large number of theoretical papers in the past (Morrison et al, 1969; Lee and Lewis, 1974; Raiche and Spies, 1981). The calculating procedure has been based on applying discrete Fourier transform methods to frequency domain models.

The computational approach of Knight and Raiche (1982) is adopted on this paper.

For the case of two concentric loops acting as transmitter (with radius á) and receiver (radius b), as in Figure 1, the mutual impedance Z is given by (Knight and Raiche 1982).

$$Z(t) = \pi\mu a b \int_0^{\infty} L_p^{-1}\left[I(p)pA_0(P,p,\lambda)\right]J_1(\lambda a)J_1(\lambda b)d\lambda \qquad (1)$$

L_p^{-1} is the inverse Laplace transform, A_0(P,p,ë) is the layered earth impedance function, P represents the conductivities $ó_i$ and thicknesses h_i of the earth model, p is the Laplace transform variable corresponding to (-iù) where ù is the angular frequency, J_1 is the Bessel function of first kind, ë is the integration variable of the inverse Hankel transform, I(p) represents the Laplace transform of the normalized current waveform, being equal to $-p^{-1}$ for step current turn-off.

The equation is solved numerically by first applying the inverse Laplace transform and then the Hankel transform.

The Gaver and Stehfest algorithm for the inverse Laplace transform is detailed by Knight and Raiche (1982) and its main steps are summarized below. The Hankel transform is evaluated by digital filtering (Anderson 1979).

For the case of coincident loop acting as transmitter and receiver, á = b, a geometrical factor Q(î) is defined as Q(î)=J_1^2(î), with î=ëa and equation (1) becomes:

$$Z(t) = \pi\mu a \int_0^{\infty} L_p^{-1}\left[I(p)pA_0(P,p,\lambda)\right]Q(\xi)d\xi \qquad (2)$$

A current step waveform is assumed, with a linear ramp current decay after switch-off in the transmitter loop. The time interval for the current to decay from its initial value to zero (turn-off time) is given by ä (turn-off time), equal to $t_1 - t_2$, where t_1 is the beginning and t_2 the end of the ramp. By taking into account the effect of the ramp, equation (2) becomes

$$Z(t) = \frac{pma}{d}\int_0^{\infty} G\left(x^2 t, a, P\right)J_1^2(x)dx \qquad (3)$$

(Raiche 1984)

where

$$G\left(x^2 t, a, P\right) = F\left(x^2 t'\right) - F\left(x^2 t\right) \qquad (4)$$

and

$$F\left(x^2 t\right) = L_p^{-1}\left|\frac{A_0(p)}{p}\right|$$

The normalized times ô and τ' are used, where

$$t = \frac{t}{sma^2} \qquad t' = \frac{t-d}{sma^2}$$, and ó

is the conductivity of the first layer.

The equation (3) is solved numerically by first applying the inverse Laplace transform using the Gaver-Stefhest algorithm, after Knight and Raiche (1982) via the following equations:

$$f(t) \cong \left[\ln(2)/t\right]\sum_{j=1}^{J} d(j,J)F\left[j\ln(2)/t\right] \qquad (5)$$

and

$$d\left(j,J\right)=\left(-1\right)^{j+M}\sum_{k=m}^{\min(j,M)}\frac{k^{M}\,(2k)!}{(M-k)!\,k!\,(k-1)!\,(j-k)!\,(2k-j)!} \qquad (6)$$

where F is the Laplace transfom of the function f.

After several tests with various models, run on a Pentium 4 based PC, the value of J was set to 8, whereas Sandberg (1990) has found an optimum value of 16 for an IBM-AT.

Function F of (4) and (5) is calculated after evaluating $A_{0,}$ the layered earth impedance function,

$$F=L_{p}^{-1}\left|\frac{A_{0}(p)}{p}\right|=L_{q}^{-1}\left|\frac{A_{0}(q)}{q}\right| \qquad (7)$$

In the case of uniform halfspace A_0 has a form of

$$A_{0}=\frac{1-\left(1+q\right)^{1/2}}{1+\left(1+q\right)^{1/2}} \qquad (8)$$

where

$$q=\frac{iwmp}{l^{2}} \qquad (9)$$

In the case of layered earth, A_0 is the reflection coefficient of the field at the surface and it is calculated via a back-substitution process from the thicknesses and resistivities of the model's layers. (Knight and Raiche, 1982; Raiche 1984).

The Hankel transform of (3) is then evaluated using the digital filtering technique by Anderson (1979).

As in electrical DC methods the apparent resistivity is used as an aid to interpretation of the voltage decay curves. It is the resistivity of an equivalent half-space that would give the same value of Z(t) as that observed in the field or calculated from a theoretical layered model. Apparent resistivity values are calculated from the impedance values via an iterative procedure which takes a first guess from the method proposed by Spies and Raiche, (1980).

FORWARD MODELS

The 2 layer case

The first category is a 2 layer model with the top layer of fixed resistivity at 10 Ohm*m, (ó$_1$=0.1 S/m) and second layer of variable conductivity. The conductivity ratio ó$_2$/ó$_1$ varies from zero (highly resistive second layer) to a value of one hundred. The loop size is fixed at 100 meters.

We first study the effect of increasing the thickness of the top layer for 25, 50, 100, to 200 meters, corresponding to ratios a/h= 0.25, 0.5, 1, 2.

The voltage values in the curves (Fig. 2) have a large dynamic range and the curves show a strong inverse dependence with time. This is the late stage of the voltage response, since the Sirotem unit is not capable at sufficiently early times to record the early times asymptote and actually in most cases it measures at late times.

During the late time stage the voltage response decays at a rate of $t^{-5/2}$, forming a straight line on a log-log graph. The voltage response is $V(t)\propto \sigma^{3/2}/t^{5/2}$, justifying the method being more sensitive to conductive than resistive targets. The response falls very rapidly with time and a threshold of 12 nV is set as a low limit in our calculations, which is the instrument noise level for the Sirotem unit. The curves with ó$_2$/ó$_1$ > 1 exhibit a local low before rising to high values, the point where they start sensing the second more conductive layer. The effect of increasing thickness is to swift this point to later times. The curves tend to coalesce up in time when the EM field is diffused to the second layer and from that point they start to deviate.

The resistivity values (Fig. 3) are more indicative of the ó$_2$/ó$_1$ variation, due to their reduced dynamic range. The most interesting feature is the “undershoot” and “overshoot” effect of the curves. The undershoot effect happens when ó$_2$/ó$_1$ <1, while the overshoot occurs when ó$_2$/ó$_1$ >1. This has important implications to the ability to resolve the resistivity of the top layer, since data must be taken before reaching this value. As it is shown in Figure 3, it is difficult to determine graphically the resistivity value of the first layer, when a/h <1. For the particular value of ñ$_1$ =10 Ohm*m the value of a/h must be one, resulting to minimum thickness of the top layer being at about one hundred meters.

The issue of selecting the optimum loop size to determine the top layer resistivity is further addressed in the following models. A 2 layer case with ñ$_1$<ñ$_2$ and ñ$_1$>ñ$_2$ is presented in Figure 4, for various loop sizes. It becomes evident that the loop size must be of the order of the thickness of the first layer, in order to determine safely the effect of the top conductive layer. A similar case is observed when ñ$_1$>ñ$_2$ in Figure 5. A top layer of 10 m thickness is totally missed when the loop size is 100 meters of side length, whereas with 25 meters loop size its effect is detectable. A minimum ratio of h/a equal to 0.2, (h is the top layer thickness and a is the loop size), is required in order the top layer to show up in the curve.

There is not any advantage of using loops of smaller size than 20 to 25 meters in resolving the first layer. In fact models run with loops of 15 and 10 meters produced similar resistivity curves. This is explained by the inherent nature of the transient induction process, which is governed by the delay time of the recording channels. A fast transmitter, sampling earlier than 50 microseconds (first channel time), is needed to sample the earth at shallow depths, up to 20 to 25 meters. The only point in decreasing the size of the loop is to map lateral inhomogeneities in earth resistivity along profiles.

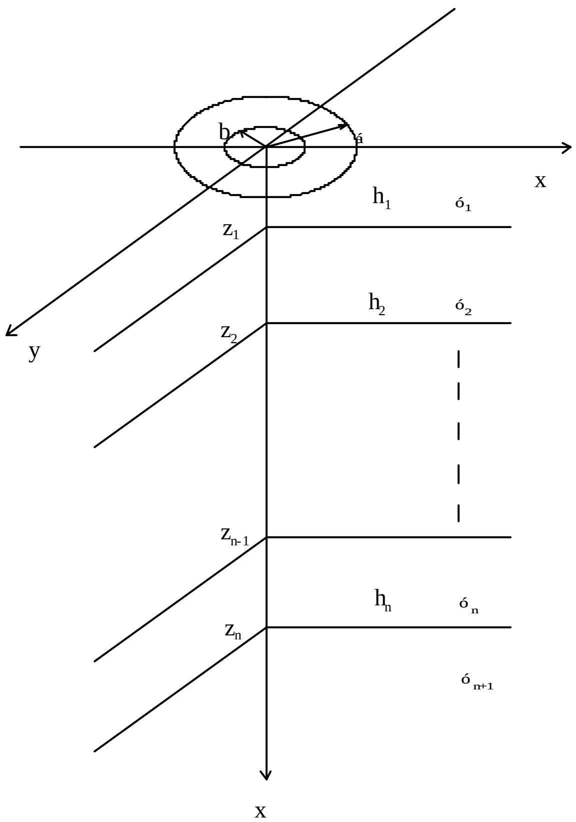

FIG. 1: Horizontally layered model

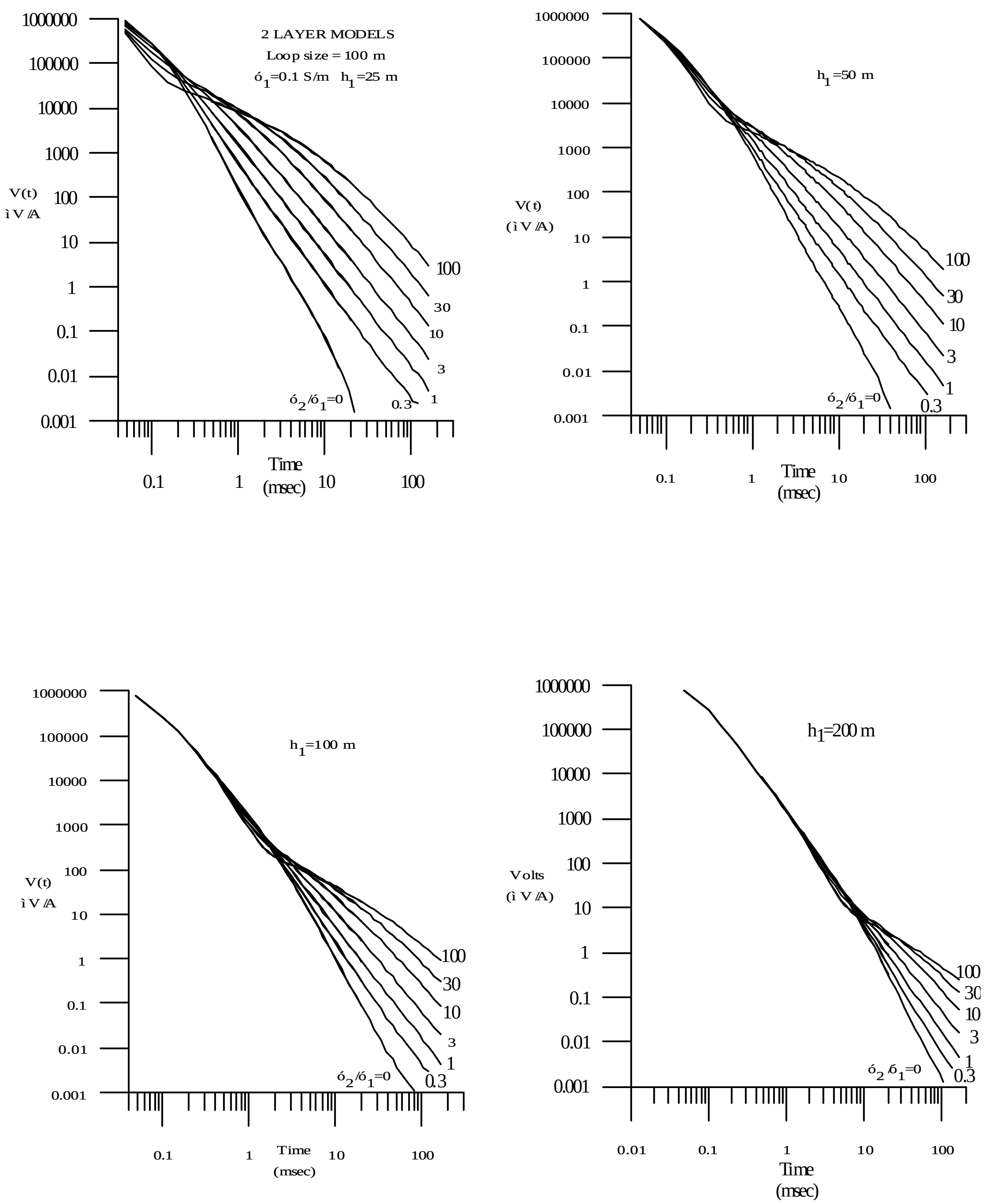

FIG. 2: Two layer models. The voltage response falls rapidly with time and exhibits a local low before sensing the second layer. The effect of increasing the thickness of the top layer is to swift this point at later times.

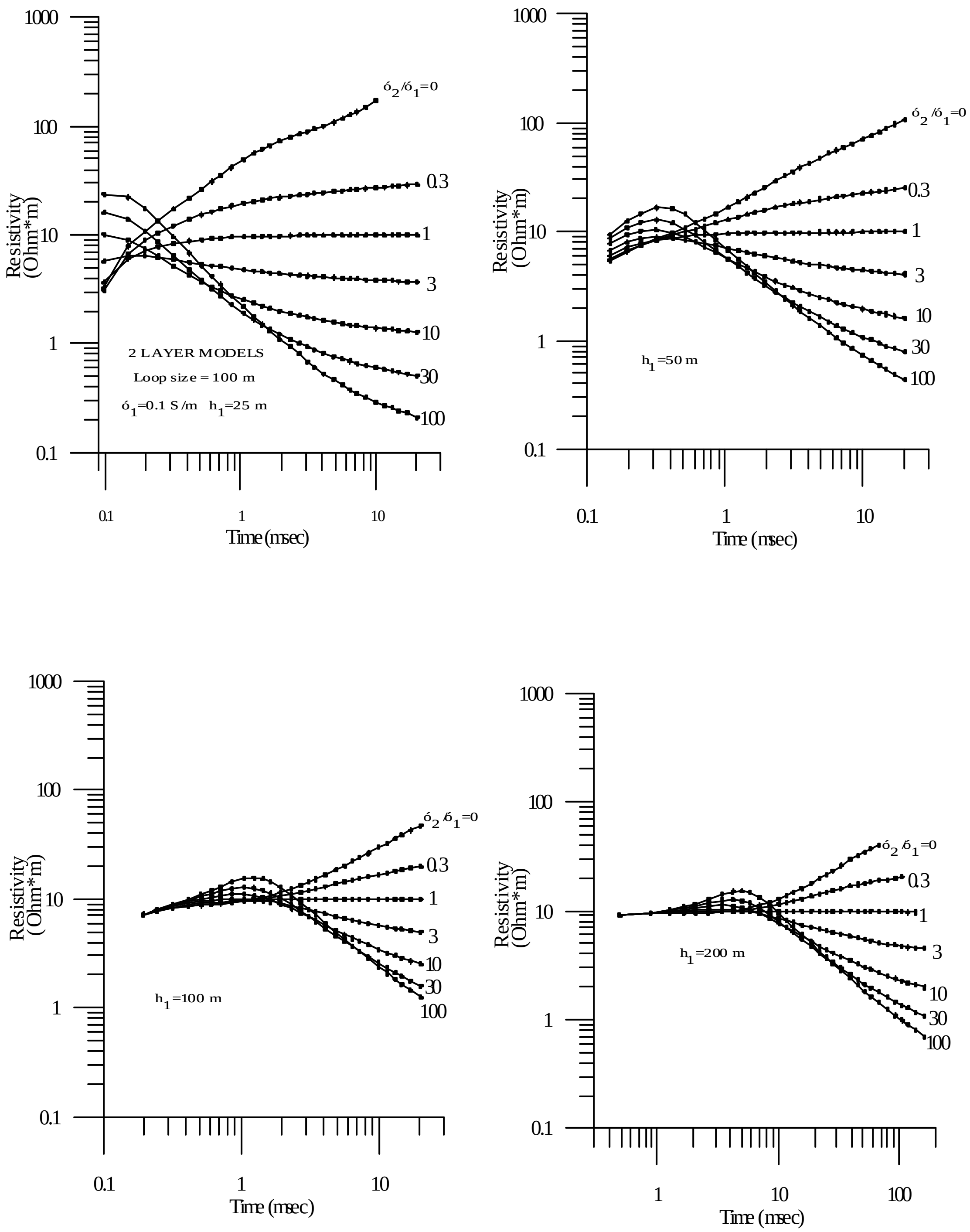

FIG. 3: Two layer models. The resistivity curves show the overshoot - undershoot feature. This is shifted at late times with increasing the thickness of the top layer.

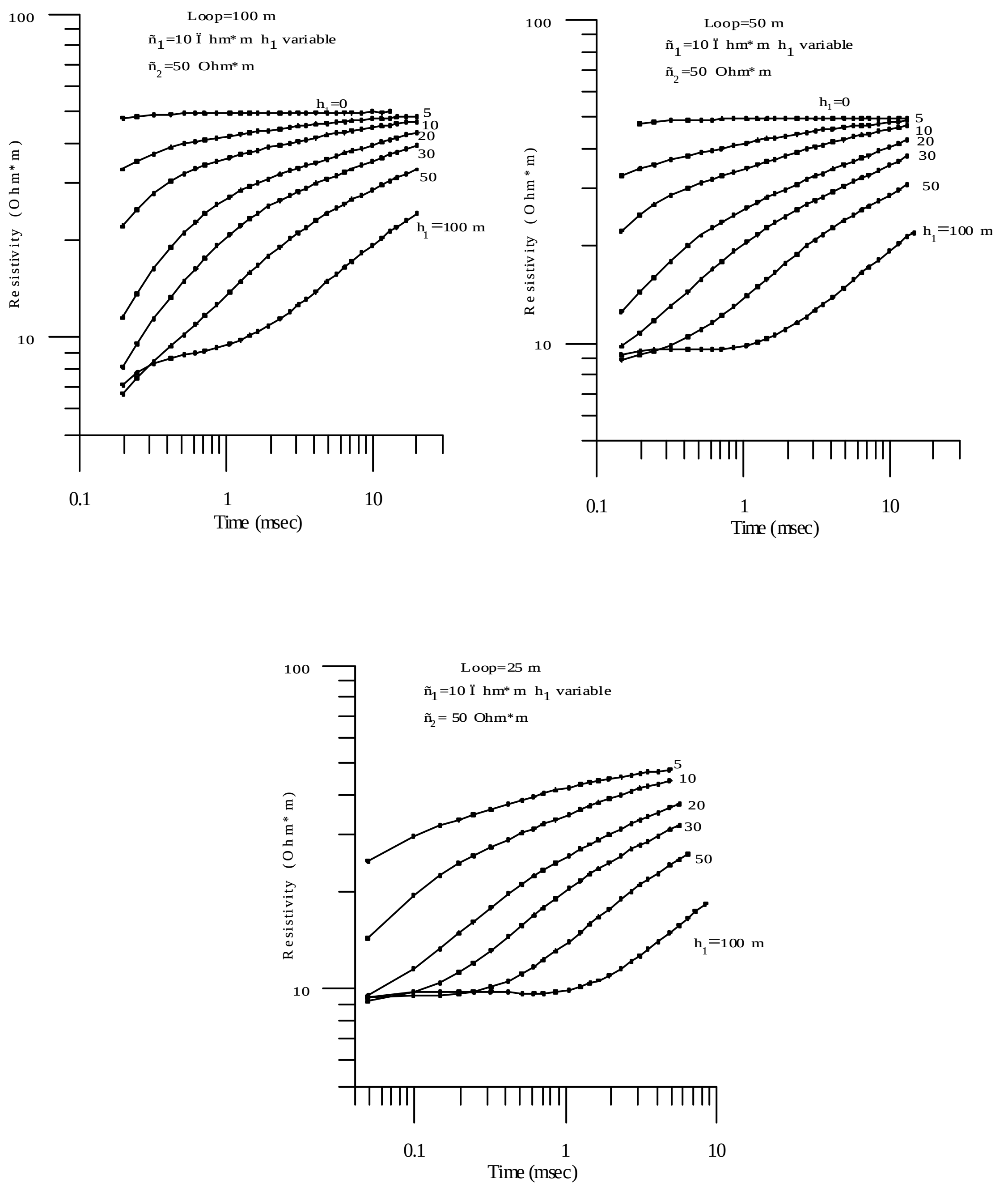

FIG. 4: Two layer models, $\tilde{n}_1<\tilde{n}_2$. The loop size must be in the order of the thickness of the top layer to resolve its characteristics.

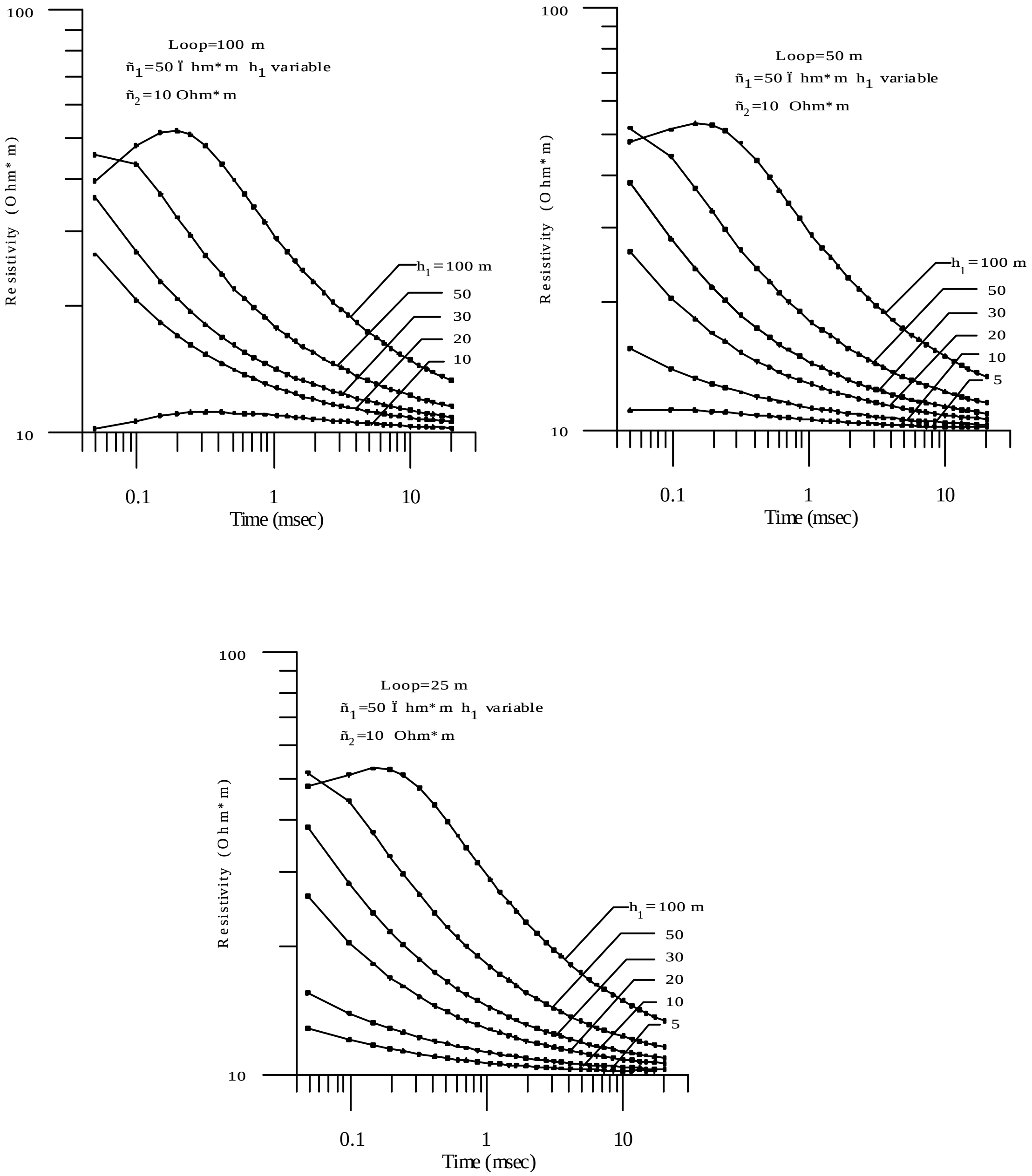

FIG. 5: Two layer models, $ñ_1$>$ñ_2$. Åffect of loop size on resolution of the first layer.

The 3 layer case

In the case of a 3 layer model we studied the detectability of an intermediate target layer of variable thickness, sandwiched in a halfspace of resistivity 100 Ohm*m. The thickness ratio of h_2/h_1 is varied from 1/5 to 1/50 and the target layer resistivity is set to10 Ohm*m, where h_2 corresponds to the thickness of the target layer and h_1 is the thickness of the top layer. The homogeneous halfspace response is also shown for comparison. The detectability in qualitative terms is expressed by the separation between the response curves of a 3 layer and a homogeneous earth.

The voltage curves are shown for various loop sizes in Figure 6. The curves coalesce at the early stage of the decay and start to deviate at intermediate times. A minimum ratio of h_2/h_1 >1/20, is required for the target layer to be distinguished from the halfspace, which in this case has a thickness of 5 meters.

By increasing the loop size from 50 to 100, 200, 400 m respectively, we simply shift the voltage response to higher values without any improvement to the ability to resolve the target layer. The only benefit is the amplitude increase of the measured signal and this might be important when an increase of the signal to noise ratio is required.

Verma and Malik (1979), in similar studies undertaken for horizontal and vertical coplanar loop transient systems, (Slingram type), have found that a conductive intermediate layer as thin as 1/14 of the top layer can be detected.

By transforming the voltage to resistivity curves, the detectability is improved and we can easily resolve a conductive target layer as thin as 1/25 of the top layer, even if a 5% noise is incorporated. There is no difference in the shape of the resistivity curves for the various loop sizes, as this is shown in Figure 7.1. The effect of increasing the thickness of the top layer in the 3 layer model curves is also shown in Figure 7.2. The resistivity curves remain the same in terms of their values, but they are shifted to later times.

In the case of a resistive intermediate layer the problem is more difficult and from the voltage and resistivity curves shown in Figure 8, it is apparent that the target layer must be thicker than 1/4 of the top layer (h_2/h_1 >1/4), in order to be detected. In this model, for a loop size of 100 m and ñ$_1$ and ñ$_2$ equal to 50 and 500 Ohm*m respectively, a minimum thickness of h_2 = 25 m is required.

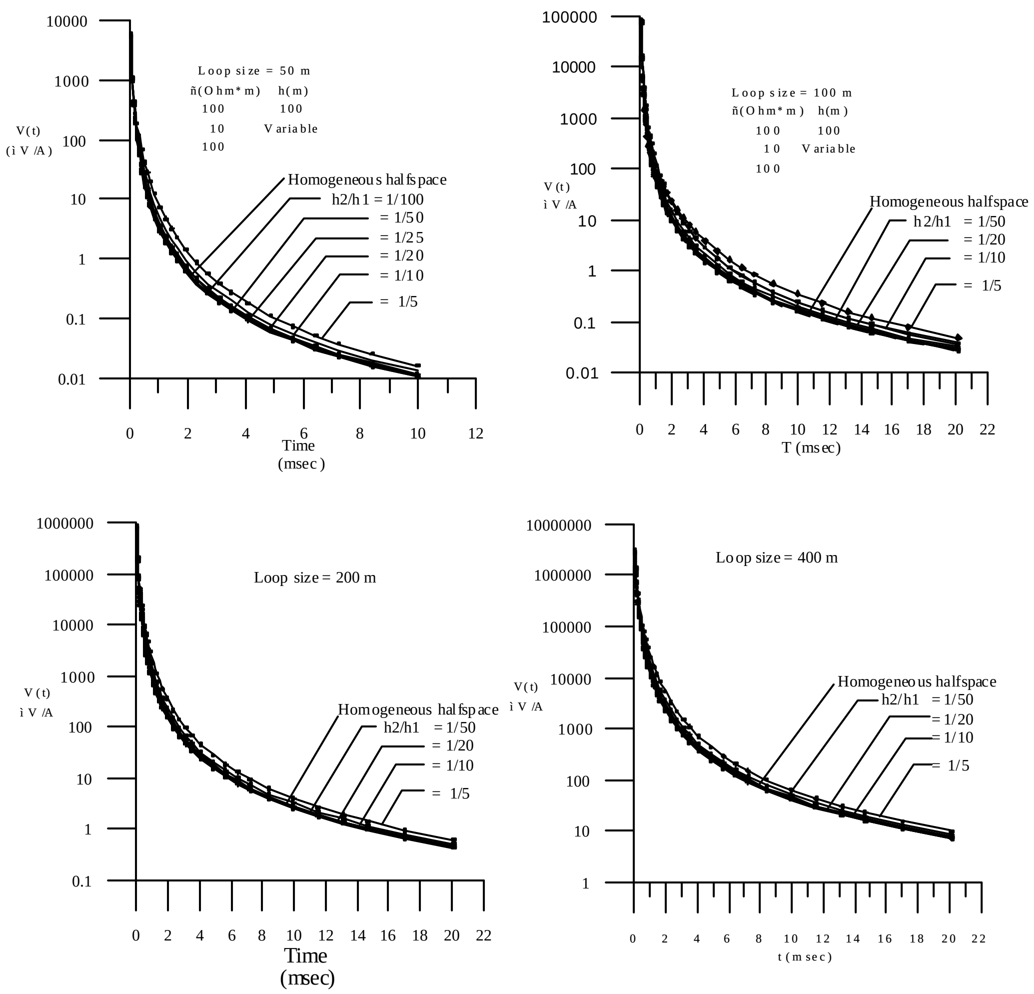

FIG. 6: Three layer models. Voltage response. A minimum ratio of h_2/h_1 >1/20 is required for the target intermediate layer to be distinguished from the halfspace.

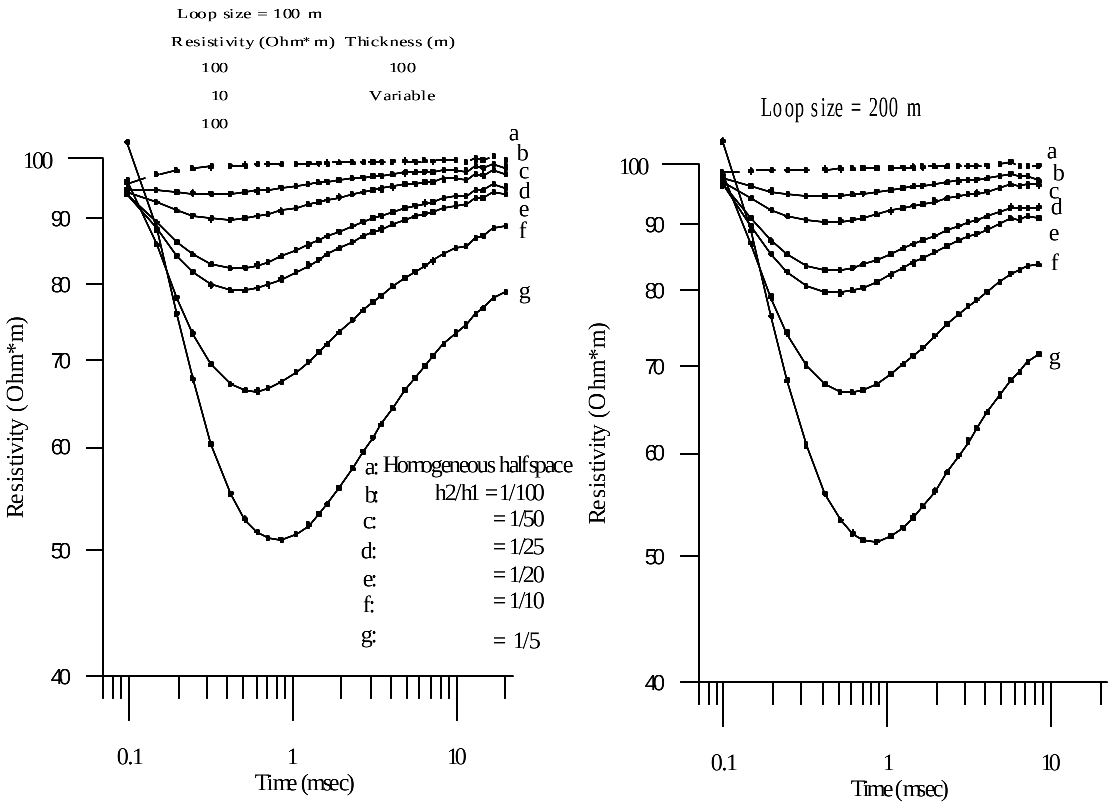

FIG. 7.1: 3 layer models. Resistivity curves of conductive layer in resistive halfspace. A conductive layer as thin as 1/25 of the the top layer can be detected.

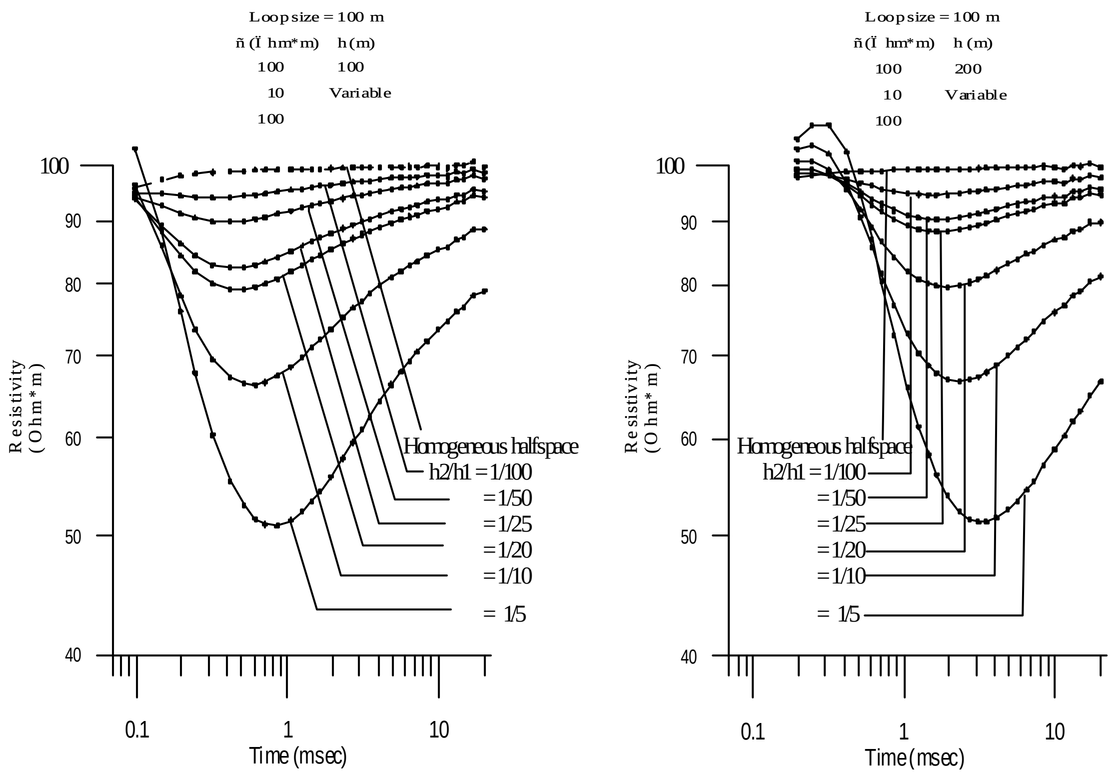

FIG. 7.2: Effect of increasing the top layer thickness

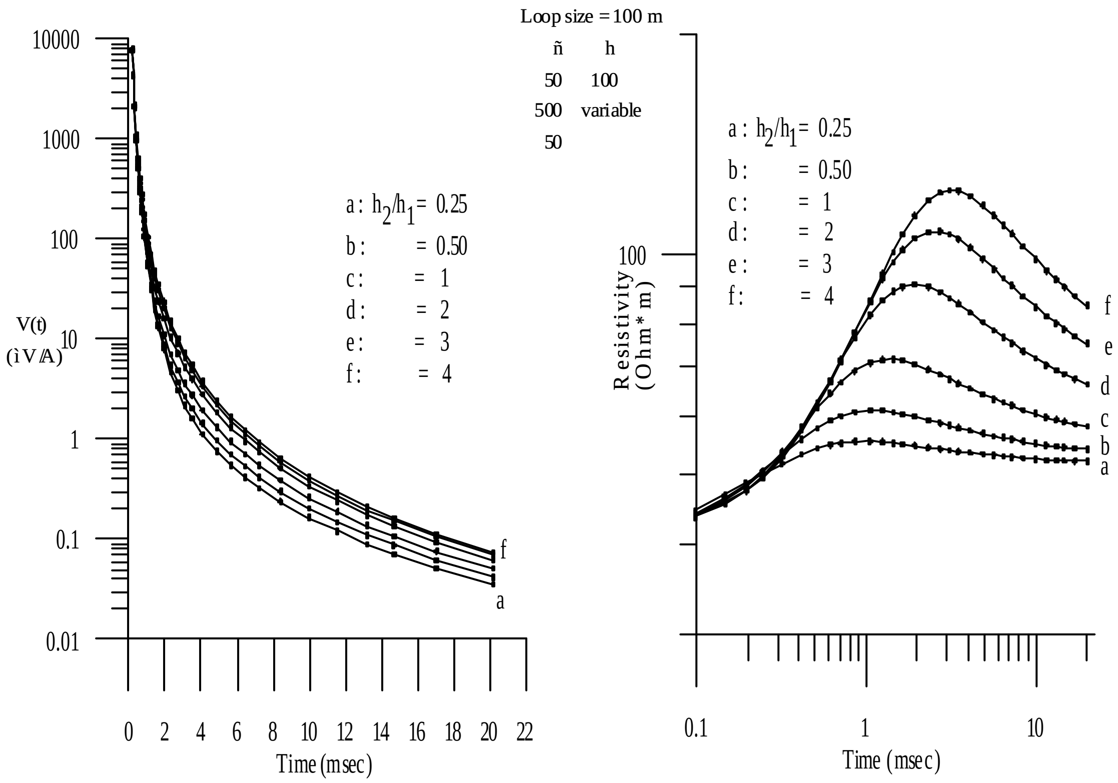

FIG. 8: Three layer models. Resistive layer in conductive halfspace. The thickness of the resistive target layer must be thicker than 1/4 of the top layer, to be detected.

Multilayer models

The ability to resolve a multilayered earth was studied next. The models start with 2 layer structure and each time one layer is added at the bottom of the sequence, resulting to three, four and finally five layers, lying on a resistive basement of resistivity 2000 Ohm*m. The overall thickness of the sequence starts from 60 (2 layer case) and ends up to 660 meters for the 5 layer case. The loop size is set to 100 meters of side length. Figure 9.1 shows the respective resistivity curves. In this case, the resistivity value of 500 Ohm*m for the fourth layer was assigned, which is a high value for the TEM technique to be distinguished from the basement of resistivity 2000 Ohm*m. Nevertheless, the 5 layer model curve is well distinguished from the 4 layer case, where the 500 Ohm*m layer is absent. This exercise indicates that the method behaves well even for such cases, unfavourable for the application of the TEM method.

For comparison purposes, we modelled the forward response of the same layer sequence using the DC method, (Schlumberger configuration), shown in Figure 9. The DC method determines accurately the resistivity of the first layer, whereas the TEM fails to reveal the presence of this layer. Its apparent resistivity values reflect the presence of the second layer, at the beginning of the measuring time interval. Apart from this, both curves resolve the five layers well, with the TEM method showing better resolution, due to its denser sampling.

With the exception of the first layer, both methods give comparable results in terms of resolution. The determination of a 5 layer sequence by the DC method, a very large expansion of the electrode array is needed, with AB/2 exceeding 800 meters. In the case of TEM, a loop of side length of 100 meters is adequate to resolve a 5 layer model with depth to the basement of more than six times its size.

We modified the resistivity of the fourth layer from 500 to 40 Ohm*m and we modelled the sequence for both the TEM and DC method. This model is a much easier target for TEM, as shown in the resistivity curves of Figure 10. The effect of the third layer of 100 Ohm*m is shown well on the TEM curve, while the top layer is completely missed.

The fourth layer is shown for thicknesses of 300, 400 and 500 meters. The curves are well separated and the five layers are well resolved. The DC models show that an array expansion of AB/2 of 1200 meters is needed to resolve the 660 meters sequence.

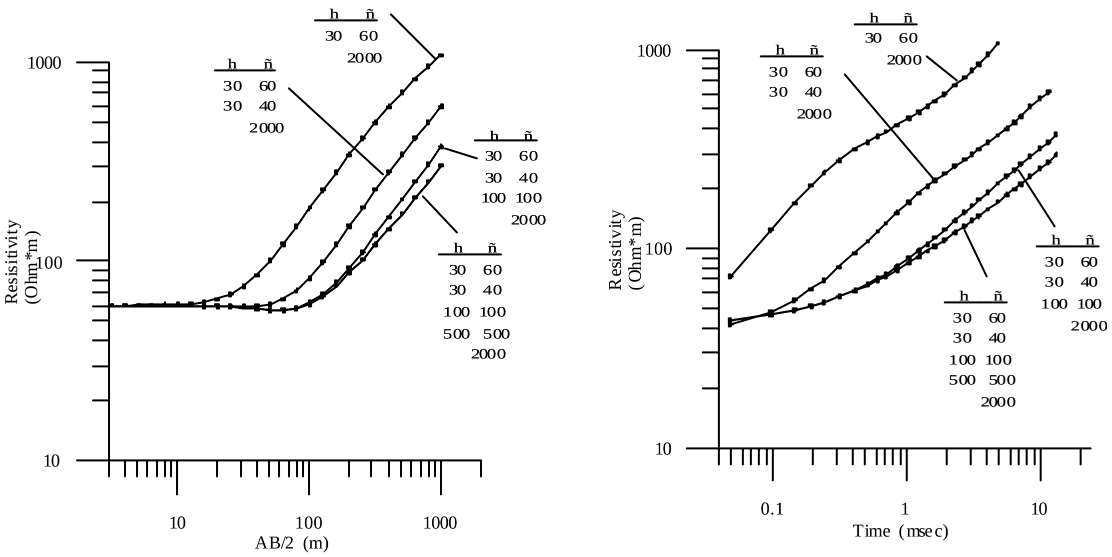

FIG. 9: Two, three, four and five layer models. Left: Electrical DC. Right: TEM

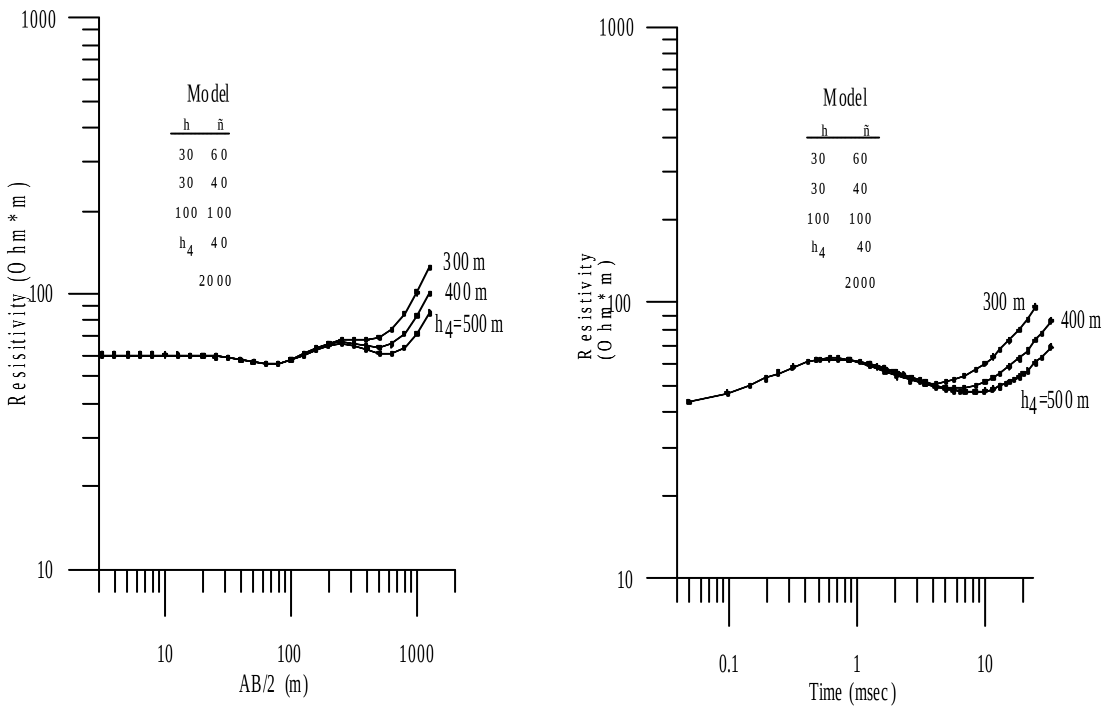

FIG. 10: Five layer model. Left: DC. Right: TEM. The top layer is totally missed by TEM but the deeper layers characteristics are well expressed.

CONCLUSIONS

Forward modeling allows us to obtain information regarding the depth of exploration, the ability to detect a target layer and help us to design the optimum survey parameters of a Transient EM sounding.

The applicability and limitations of transient EM soundings were revealed from the analysis of the theoretical data presented and several conclusions were drawn.

The resistivities versus time curves are more indicative of the conductivity variation, due to the reduced dynamic range of the resistivity values. The “undershoot” and “overshoot” effect of the curves have important implications to the ability to resolve the top layer resistivity, since data must be taken before reaching this value.

In order to determine the resistivity of the first layer the loop size that is used must be in the order of the layer thickness. There is a limit to the minimum layer thickness of the top layer of about twenty to twenty five meters, set by the earliest channel time of the TEM unit.

In three layer cases with $ñ_2/ñ_1$ =0.1, the method can detect intermediate conductive layers as thin as 1/25 of the thickness of the first layer and as thin as 1/4 of the top layer when the target is resistive ($ñ_2/ñ_1$ =10).

There is not any advantage in increasing the loop size, other than increasing the signal to noise ratio. A combination of a small and a large loop setup should be used, in order to determine both the shallow and deep part of the sequence.

The method has certain advantages compared to the traditional Electrical DC methods, in terms of logistics and space size needed to conduct the survey. The depth of exploration is much larger and as it was found by modelling, a layered sequence of thickness much larger than the loop side length can be investigated.

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