Anomalous field and apparent resistivity in transient EM sounding

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Introduction

The fundamental idea of electric prospecting with d.c. controlled source was first formulated by Schlumberger in France and at about the same time by Wenner (1917) in USA. The idea was to compare the summary electric field due to non-uniform medium (half-space) with the normal field of the same electrode configuration due to uniform medium and to use the noted differences for examining the geo-electric structure of the non-uniform medium. This idea keeps its value till today (Kunetz, 1966).

The comparison above could be made in two different ways: to calculate the difference between summary and normal fields and thus to determine the anomalous field (similar to the most of other geophysical methods), or to calculate the so-called apparent resistivity. The last way had been chosen.

According to its definition, the apparent resistivity

$$\rho_A = K\frac{\Delta V}{I} = \rho_1 \frac{\Delta V}{\Delta V_1}, \qquad (1)$$

where K is the configuration coefficient, ΔV and ΔV_1 are the voltagess at measuring electrodes on the surfaces of non-uniform and uniform half-space correspondingly, and I is the current through the current electrodes.

Therefore, the calculation of the apparent resistivity equivalents to the normalisation of the initial summary field or corresponding voltage (signal) values by the normal field (signal) values. The ratio is rendered in addition the dimension of resistivity.[2]

The ratio and the difference are interconnected by the correlation

$$F / F_1 = (F - F_1)/F_1 + 1, \qquad (2)$$

where F may be any component of the field.

Geo-electrics started with examination of lateral change of medium resistivity, in other words, with profiling. Since the normal field F_1 is in profiling constant, the shapes of profiling curves for both the ratio and difference are the same.

However, the examination of vertical change of medium resistivity, i.e. vertical sounding, soon started in which the apparent resistivity was also introduced (Hummel, 1929 et al.).

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[2] By using the same approach other apparent parameters can be also introduced, by the way: apparent density in gravimetry, or apparent susceptibility in magnetics etc.

Quite probably, it was done automatically due to the vividness of this manner of presenting geo-electric data. Later on the apparent rseistivity was also introduced into electromagnetic, in particular magneto-telluric, sounding (Cagniard, 1953):

$$\rho_A = \frac{1}{\omega\mu}|Z|^2 = \rho_1 \frac{|Z|^2}{|Z_1|^2}, \tag{3}$$

where Z and Z_1 are input impedances of non-uniform and uniform half-spaces, $\omega = 2\pi / T$, T is the period of field oscillations, and $\mu = \mu_v = 4\pi \cdot 10^{-7}$ H/m.

In case of sounding the normalising field F_1 in (2) is not constant as in case of profiling and decreases with the increase of parameter controlling the sounding depth (spacing, period of oscillations, or transient time). Due to this the two manners of presenting the information as mentioned above are not more equivalent. The calculation of the difference does not disturb very much the shape of the initial (non-transformed) field or signal sounding curve. In particular, all the non-monotonous changes of one and the same name of both summary and anomalous field take place at the same positions on the horizontal axis. In case of calculating the ratio both the amplitude and shape of any changes of the field (in particular the amplitude and shape of any extrema) are distorted, as well as their positions at the horizontal axis are shifted to the right. Therefore, the disfigured information is used in the further interpretation. Nevertheless, the interpretation made using the matching method is not incorrect since the disfigured experimental sounding curve is compared with synthetic curves disfigured in the same way. It does not mean, however, that it is not important to investigate the disfigurations above.

The short and by far not the complete historical sketch above was given to try to show why no attention was paid to these distortions during a period of several dozens of years. As far as we know, the parameter of apparent resistivity has been only criticised by Semenov (1986 and earlier publications) from two main points: the absence of any special reason to present geo-electric information in a very different form compared to other geophysical methods like gravimetry or magnetics etc. (1), and the possibility to obtain senseless results (e.g. negative apparent resistivity) in some special cases (2). This criticism did not receive much attention and apparent resistivity still remains the most useful form of presenting geo-electric and electromagnetic data, especially of sounding data.

To our opinion, the disfigurations above related to the use of the apparent resistivity result definitely in the *artificial* elimination of the sounding depth and quite probably of the vertical resolving power. They are common for any type of sounding, but the degree of distortions may be different which makes them separate subjects to research in each separate case. In this particular paper the disfigurations of the sort will be only demonstrated by using simple 1D examples(Kamenetsky, 2000) of modelling transient electromagnetic sounding (TEMS or TS), as well as d.c. sounding for the comparison.

Apparent resistivity in transient sounding

The sounding depth and vertical resolution of TS are subjects of research by many authors in their aim to explain the higher vertical resolution of TS which is often experimentally observed and can not be explained in frames of classic electrodynamics (the so-called high-resolving electromagnetics phenomenon or HRE). In particular, many attempts were made to explain HRE by the influence of induced polarisation or IP (e.g. Ageev and Svetov, 1999 et al.), but still the mechanics of the phenomenon are not fully disclosed. If the IP effects or other adjustings are not considered, then the low resolving power of TS curves is normally explained by such a *natural* factor as the integral character of the quasi-stationary electromagnetic field.

Let the azimuth electric field component E be due to a vertical magnetic dipole (VMD) measured at the surface of the horizontally-layered half-space (with N as the number of layers and corresponding index of values bellow) at the distance r from VMD. The VMD moment $M=IQ$ (I is the current in A and Q is the effective area in sqr. m). In case of uniform half-space with conductivity σ_1 the electric field

$$E_1 = Me_1 / \left(2\pi\sigma_1 r^4\right), \tag{4}$$

where

$$e_1 = 3\left[\Phi(u) - \sqrt{\frac{2}{\pi}} u e^{-u^{2/3}} \left(1 + u^2/3\right)\right], \tag{5}$$

$\Phi(u)$ is the probability integral,

$$u = r\left(\frac{\sigma_1 \mu}{2t}\right)^{1/2}, \tag{6}$$

and t is the transient time.

Apparent resistivity (or conductivity) can be calculated by early stage, late stage, or all-time formulae, which is of not a principle importance. We will use the late stage one. Then $t \rightarrow 0$, $u \rightarrow \infty$ and

$$E_1 = \frac{IQr}{40\pi^{3/2}} \sigma_1^{3/2} \left(\frac{\mu}{t}\right)^{5/2}, \tag{7}$$

from which the conductivity of the uniform half-space

$$\sigma_1^* = \pi\left(\frac{40E_1}{IQr}\right)^{2/3}\left(\frac{t}{\mu}\right)^{5/3}. \tag{8}$$

The index (*) is used here since the value found in this way is less than the true conductivity σ_1 at the early stage of the transient where the late stage formula is not valid.

The apparent conductivity of the N-layered medium is calculated in the same way, so that

$$\sigma_{AN} = \left(\frac{40E_N}{IQr}\right)^{2/3}\left(\frac{t}{\mu}\right)^{5/3} = \sigma_1^*\left(\frac{E_N}{E_1}\right)^{2/3}. \tag{9}$$

Therefore, the normalisation also takes place here of the summary field due to the horizontally-layered medium by the normal field due to the uniform medium. The latter decays with transient time, which results in a disfiguration of the apparent conductivity transient sounding curve. We will show this by using modelling data[3] obtained for a three-layered model. The resistivity of the model upper layer equals the resistivity of the basement $\rho_3 = \rho_1$. The resistivity of the intermediate layer may be both more and less compared to the ρ_1 value.

Three-layered model with conductive intermediate layer

Let the three-layered model is investigated with parameters:

h_1/h_2=1000/100 m, $\rho_1/\rho_2/\rho_3$=100/10/100 Ohm·m.

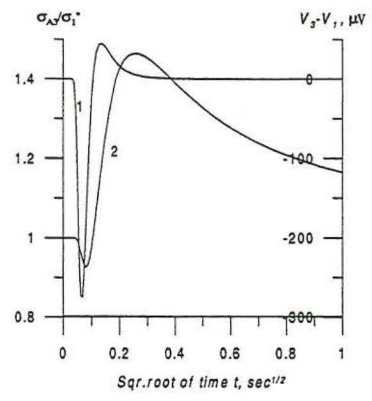

Fig. 1. Transient sounding curves of the 3-layered model with conductive intermediate layer:
1 - anomalous field, 2 - apparent conductivity.

Parameters of the configuration: I=100A (or 10 A and 10 turns), Q=10^5 sqr.m (the loop ca 300x300 m), the length of measuring dipole MN=100 m.

Thus, to obtain the voltage at MN in μV it is necessary to multiply the electric field (calculated in V/m for I=Q=MN=1) by $100 \cdot 10^5 \cdot 100 \cdot 10^6 = 10^{15}$. The voltage in the receiver loop of radius r (or in the small receiver loop at the centre of loop-in-loop configuration, in accordance with the reciprocity principle) can be also found in the same way, if to replace MN by $2\pi r$.

Results of modelling are given in Fig. 1 in forms of two curves: curve 1 of anomalous voltage $\delta V_3 = V_3 - V_1$ and curve 2 of relative apparent conductivity $\overline{\sigma}_{A3} = \sigma_{A3}/\sigma_1^*$. The

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[3] The data are obtained with the program of Prof P.Weidelt (Technical University of Braunschweig, Germany)

commonly used square root of transient time is chosen for the horizontal axis. To avoid additional wrong impressions the logarithmic scales are not used.

The curve 2 of apparent conductivity starts and ends with unity. The intermediate conductive layer displays itself mainly by the right maximum with the amplitude 46% at the transient time $t_{\sigma_A max} = 63$ ms.

The curve 1 of anomalous signal starts and ends with zero. The main features of this curve (compared to the curve 2) are as follows:

1. Amplitude of the left extremum is much more than of the right one (v.v. to the curve 2),
2. Curve 1 is compressed in time (curve 2 is stretched),
3. Curve 1 is shifted to the left along the time-axis (curve 2 to the right).

The main influence of the conductive intermediate layer on the anomalous signal is demonstrated by the left minimum with the amplitude of 275 μV at the transient time $t_{\delta V\, min}$=4.6 ms.

Table 1. Parameters of transient curves with the conductive intermediate layer

	Parameters of TS curves	δV_3	$\overline{\sigma}_{A3}$	Ratio of parameters
	1	2	3	4
1	Width of the main extremum at the 0.5 level, ms	4.7	507	1/108
2	Delay-time of the main extremum, ms	4.6	63	1/14
3	Normal field signal V_1 at the point of the main extremum, μV	3375	8	422
4	δV_3 at the point of the main extremum, μV	-275	6	46

Detailed parameters of curves under comparison are given in Table 1. They demonstrate obvious advantages of curve 1 and disadvantages of curve 2, which can be formulated in the following way. One and the same layer at one and the same depth displays itself at earlier delay-times for the anomalous field compared to the apparent resistivity. That means a dipper layer can display itself for the anomalous field compared to the apparent resistivity at one and the same delay-time. Since the depth of TS relates directly to the value of delay-time, one can state that the depth of sounding based on use of the anomalous field can be more than that of the apparent resistivity. It is probably more accurate to state that the inversion of sounding data by use of subtracting the normal field (instead of transforming the summary field into apparent resistivity) makes it possible to realise the higher depth of sounding inherent to the initial data set, which possibility is lost in case of using the apparent resistivity.

The use of the anomalous field brings also very important energetic advantages due to a higher level of the measured signal at earlier delay-times, which makes it possible to eliminate configuration dimensions, the weight of wire and batteries etc. For example, in the case above the maximum amplitude of the anomalous field signal and the amplitude of the normal field signal at the same point reach hundreds and thousands of micro-Volts correspondingly, whereas only units of micro-Volts at the point of maximum of the apparent conductivity. The latter might be non-measurable ones against the background of a certain level of noises, and important features of sounding curves cold not be detected.

We have to remember now that both anomalous field and apparent resistivity (or difference and ratio) are obtained from one and the same initial data set with one and the same intrinsic information content. Moreover, the difference and the ratio are interconnected by the correlation (2) and can be calculated one from the other. Then a doubt arises naturally whether all the advantages above of using the anomalous field are really possible.

To our mind, the explanation is quite clear. The initial data set is a simple mixture (just the sum) of normal and anomalous field. While using different transformations of the initial data the different redistribution of the intrinsic information along the horizontal axis (or in transient time in TS) takes place. In case of the difference the information about the normal field is excluded. In case of the ratio the more complicated mixture (compared to the initial summary field) is obtained in which the early- and medium-stage information related to the intermediate layer is suppressed, but the late-stage is emphasised. Therefore, the initial information is in the last case not lost, but not used in the best way.

This position has a special meaning in case of TS. The minima of curves 1 and 2 correspond to the wave part (proportional to resistivity) of the transient field due to the intermediate layer, and the maxima correspond to the induction one (proportional to conductivity). The wave part is much more intensive compared to the induction one. Transformation of the field into apparent resistivity reverses these proportions. In other words, the wave phenomena prevail in the anomalous field sounding curve, and the induction ones in the curve of apparent conductivity. Advantages of using the wave part are seen from the example above. Perspectives of investigating the wave (or "quasi-wave") transient field are validated also by analytical and modelling data examined in the work of Gubatenko et al. (2000).

Three-layered model with resistive intermediate layer

Let the three-layered model now have the higher resistivity of the intermediate layer ρ_2=1000 Ohm·m. Other parameters of the model and configuration are the same. Results of modelling are shown in Fig. 2 with the same notations. Parameters of curves under comparison are given in Table 2.

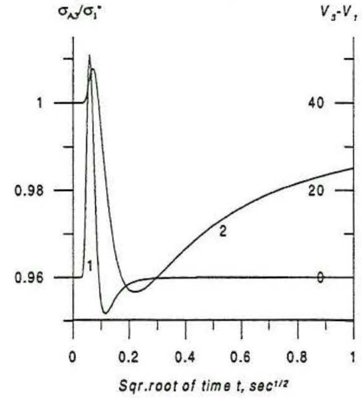

Fig. 2. Transient sounding cueves of the 3-layered model with resistive intermediate layer:
1 - anomalous field, 2 - apparent conductivity.

The influence of the resistive intermediate layer is naturally less compared to the conductive one. Maxima and minima change over their positions. Other effects are similar to those of the previous case: the compression and shift to the left along the time axis. Ratios of curve parameters are also of the same order as in the previous case. Therefore, the increase of the sounding depth and vertical resolution is in this case also expected.

Table 2. Parameters of transient curves with the resistive intermediate layer

	Parameters of TS curves	δV_3	$\overline{\sigma}_{A3}$	Ratio of parameters
	1	2	3	4
1	Width of the main extremum at the 0.5 level, ms	3.4	494	1/145
2	Delay-time of the main extremum, ms	3.4	59	1/17
3	Normal field signal V_1 at the point of the main extremum, μV	6169	9	685
4	δV_3 at the point of the main extremum, μV	51	-0.6	85

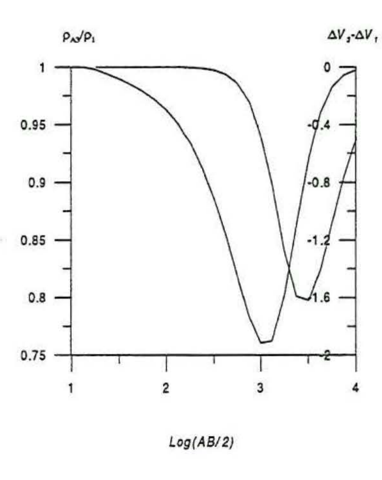

Fig. 3. D.c. sounding curves of 3-layered model with conductive intermediate layer:
1 - anomalous field, 2 - apparent resistivity.

D.c. sounding of the three-layered model

It is interesting to compare the effects obtained above for the transient electromagnetic sounding with similar effects (if any) in case of d.c. sounding of the same three-layered model. We shall confine ourselves with the model with conductive intermediate layer. Results of modelling for Schlumberger configuration are given in Fig. 3, and parameters of curves in Table 3.

To the contrary of TS, the wave part is naturally absent and the extrema of the same name are to be compared.

Table 3. Parameters of d.c. curves with the conductive intermediate layer

	Parameters of d.c. curves	δE_3	$\overline{\sigma}_{A3}$	Ratio of parameters
	1	2	3	4
1	Width of the extremum at the 0.5 level, m	2400	6000	1/2.5
2	AB/2 value of the extremum, m	1100	3100	1/3
3	Normal field E_1 at the point of the extremum, μV/Am	32	3	10
4	δE_3 at the point of the extremum, μV/Am	-1.9	-0.6	3

The effect is, therefore, not so strong in this case compared to TS. Nevertheless, the 3-times less spacing is needed to reach the same d.c. sounding depth in case of using the anomalous field instead of apparent resistivity (compare positions of minima of curves 1 and 2).

Conclusions

Examples described above display perspectives of using in geo-electrics and electromagnetics the anomalous field instead of the extraordinary used apparent resistivity. This enables us to get the information related to a certain features of subsurface structure at smaller values of parameters controlling the sounding depth. An increase of the sounding depth and quite probably of the vertical resolution is therefore expected.

The effect is especially intensive in transient sounding, where the wave phenomena prevail in the anomalous field compared to induction ones prevailing in the apparent resistivity. The phenomenon of high-resolving electromagnetics may be probably explained in frames of the classic theory in this way. The further modelling of different situations is to be continued for corroborative examination of these expectations. The testing of the approach suggested on the basis of field experimental data is needed as well.

The effect is not so strong in d.c. sounding. Nevertheless, the 3-times less spacing is needed to reach the same sounding depth. The same effects are possible in other types of electromagnetic soundings, as well as in the electric and electromagnetic well-logging.

To introduce the method suggested of presenting geo-electric and electromagnetic data a certain reconstruction of the interpretation procedure is needed which, to our mind, will not meet principle difficulty. In particular, the normal field can be determined by calculating it for different values of resistivity of the uniform half-space and minimising the difference between calculated and observed curves.

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