Transient Electromagnetic Responses of High-Contrast Prisms in a Layered Earth

Gregory A. Newman and Gerald W. Hohmann

Department of Geology and Geophysics
University of Utah
Salt Lake City
Utah 84112-1183, USA

Summary

A numerical solution has been developed for transient electromagnetic (TEM) responses of prisms in a layered host. The solution is based on the method of integral equations, where the prisms are replaced with an equivalent scattering current. This scattering current is approximated with pulse and divergence-free basis functions. The divergence-free functions model eddy currents closed in the prisms, and hence simulate the inductive responses of the prisms in a very resistive host. Checks on the solution show that it is valid for conductive and resistive hosts, including a free-space host.

The masking effect of conductive overburden is shown to delay and suppress the three-dimensional (3-D) TEM response of a conductor. After the overburden response is removed, an interpretation of the conductor with free-space models is a poor approximation when the basement rock is conductive. Instead of an exponential decay at late times, the conductor's response decays as an inverse power law. When the basement resistivity is increased, the conductor exhibits an exponential decay at late times.

We have used the solution to gain interpretational insight into the lateral resolution of multiple conductors with different TEM surveys. The resolution of multiple conductors is very poor in a fixed-loop survey, but in a central-loop survey the resolution is better, provided the data are interpreted at early times. At later times, multiple conductors may not be resolvable and interpretational ambiguities could arise in a central-loop survey.

Numerical solution

An integral equation solution for the transient electromagnetic (TEM) scattering of prisms in layered half-spaces is formulated to provide meaningful results when the prisms are in highly resistive layers. This solution, developed by Newman and Hohmann (1987) replaces the prism with an unknown scattering current. The scattering current is then approximated with pulse and divergence-free basis functions in the frequency domain. Divergence-free basis functions model eddy currents that exist in confined bodies in a very resistive host and hence simulate the inductive responses of the prisms. A Galerkin solution for the scattering current is then obtained where the dominant charge operator is eliminated from part of the solution by integrating the tensor Green's function around the rectangular paths of the divergence-free basis functions. With the solution of the scattering current, the electric and magnetic fields scattered by the prisms are then calculated, and the corresponding TEM responses are obtained by inverse Fourier transformation. The resulting solution provides meaningful results over a wide range of layered-host resistivities, including that of free space.

Conductive overburden and target detectability

One way to illustrate the influence of conductive overburden on target detectability is to compare responses of a target in a highly resistive half-space with and without overburden. In Fig. 1 we consider a 10 S/m prism, 25 m thick embedded in a 10 000 Ω.m half-space. Its depth of burial, depth extent and strike length are 100, 100 and 800 m, respectively. The prism is centred at x = 0 m in the profile; the transmitter loop is 500 m on a side with its near wire located at x = −250 m. Profiles in Fig. 1, based on a step shut off of the transmitter, clearly show the position of the prism from early to late times.

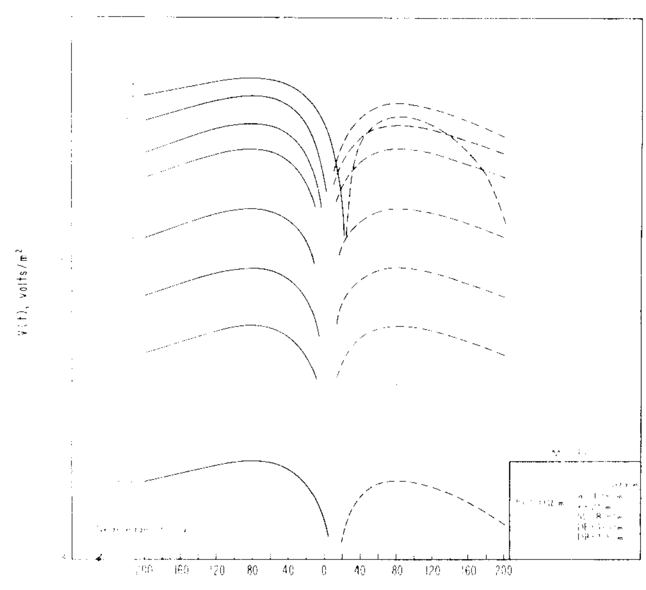

FIGURE 1
Profile of the vertical component of voltage calculated for a prism in a 10 000 Ω.m half-space.

Figure 2 shows the profound effect of conductive overburden on target detectability when the prism is buried beneath a 10 Ω.m overburden 50 m thick (compare Fig. 1 with Fig. 2). Conductive overburden limits the time range in which the prism is detectable; the prism is detectable in only 3 of the time channels shown: 10, 15 and 20 ms. This suppression of the prism response at early times has been called by Lamontagne (1975) 'overburden blanking'. According to

Nabighian (1987), the delay in the prism response is inversely proportional to the conductivity-thickness product of the overburden and the overall dimensions of the measuring system.

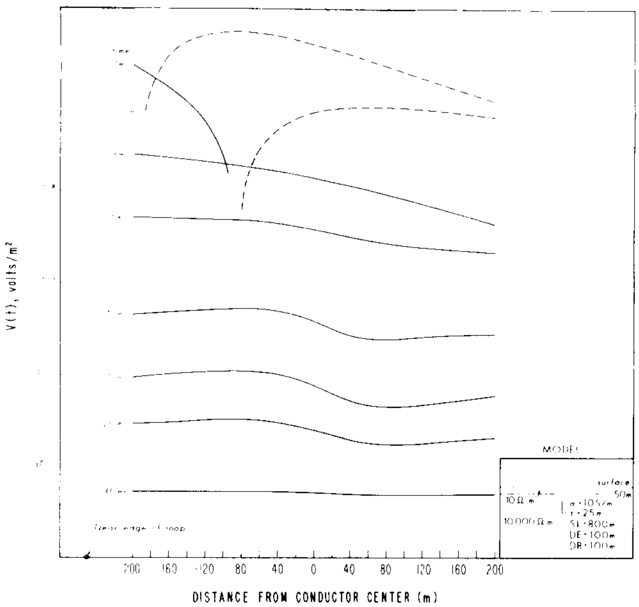

FIGURE 2

Profile of the vertical component of voltage calculated for a prism in a 10 000 Ω.m half-space with a 10 Ω.m overburden, 50 m thick.

A complete interpretation of the prism response is possible when the overburden response is removed from the profile in Fig. 2. Figure 3 compares the responses of the prism with overburden response subtracted for basement resistivities of 10 000, 1000 and 100 Ω.m at x = −80 m. After 10 ms, the responses of the prism are identical for the 10 000 and 1000 Ω.m basements; they decay exponentially with estimated time constants of 3.3 ms. However, this is not the case for the prism in the 100 Ω.m basement. The response of the prism in the 100 Ω.m basement does not decay exponentially. Rather, its decay is an inverse power law with a fall off of t^{-4} for the latest times shown in Fig. 3. This decay is consistent with the late-time response of a confined conductor in a conductive medium, where the late time response can be represented as an inverse power, i.e. $O(1/t^{v})$, which is characteristic of the host rock (Nabighian, 1987). Even though the responses of the prism in the 1000 and 10 000 Ω.m basements decay exponentially and at the same rate as that of the prism in free space, free-space interpretations of these responses are biased. The overburden increases the amplitude of the prism's response at all times in comparison to the response in free space.

Resolution of two conductive prisms with TEM surveys

Numerical models can contribute interpretational insight into the lateral resolution of multiple conductors. Obviously, many multiple targets for different host layering and survey configurations can be modelled with our solution. However, the scope of our study is intended only as a preliminary survey and we will study the TEM response of two prisms in a resistive half-space for the fixed-loop and central-loop configurations. We will discuss the resolution of both conductors, paying particular attention to survey design.

Figure 4 shows the vertical response of two prisms in a 1000 Ω.m half-space for a fixed-loop configuration. The profiles are at seven different times; ranging from 0.5 to 30 ms. Both prisms are identical in their sizes, depths and conductivities and are the same as the prism in Fig. 1. One prism is positioned at x = 0 m and the other at x = 80 m, and the fixed-loop transmitter is once again 500 m on a side with its near wire located at x = −250 m.

At early times, 0.5 and 1 ms, and at late times, which include 15, 20 and 30 ms, the response of the 1000 Ω.m half-space is visible in Fig. 4. The half-space response is important at late times because it is slower to decay than the response of the two prisms. If the response of the half-space is not considered in an interpretation, the migrating crossover at intermediate and late times in Fig. 4 indicates a dipping conductor. However once the half-space response is subtracted from the profile, a vertical conductor is then interpreted at x = 30 m with a time constant of 3.7 ms. The fixed-loop configuration fails to distinguish the individual prisms, even when the half-space response is removed.

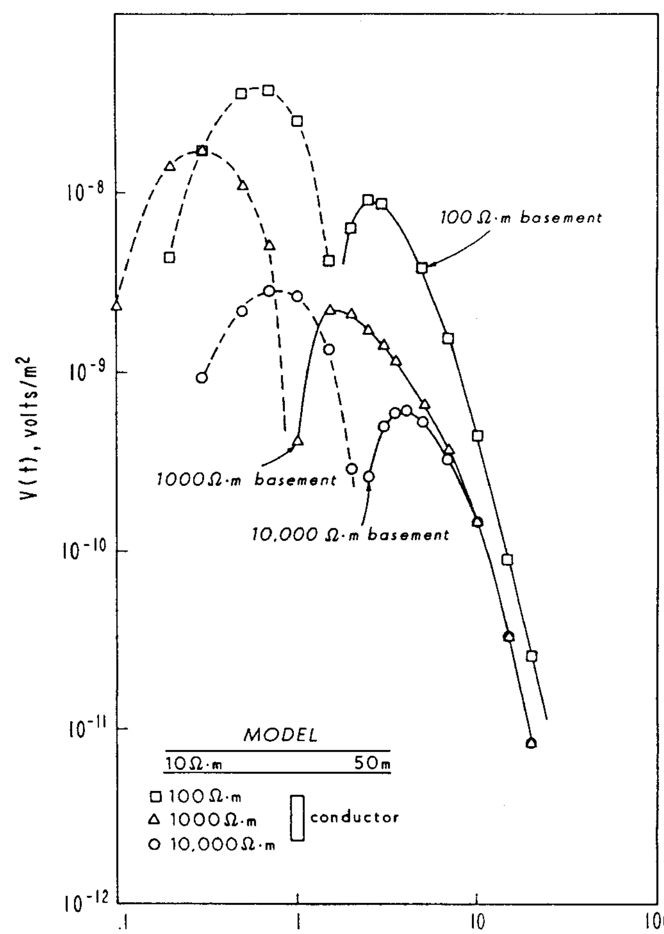

FIGURE 3

Comparison of the scattered vertical field decay for variable basement resistivity with overburden. The 10 Ω.m overburden is 50 m thick. The basement resistivity varies from 10 000 to 100 Ω.m.

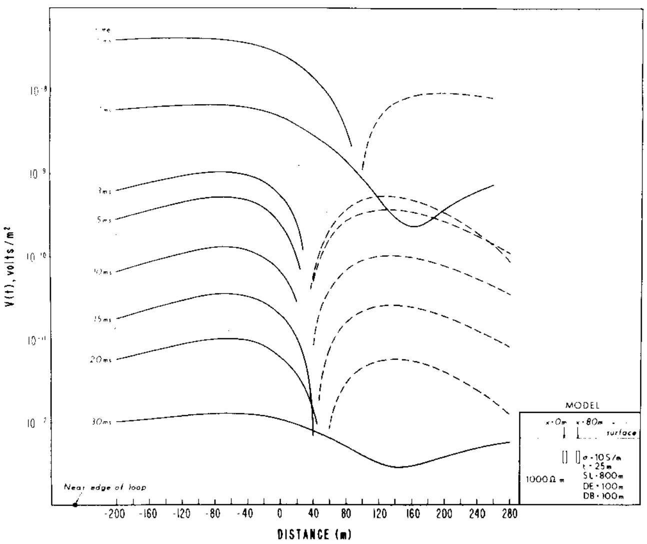

FIGURE 4
Profile of the vertical component of voltage calculated for two prisms in a 1000 Ω.m half-space for a fixed-loop configuration. On the surface, one prism is located at x = 0 m and the other prism at x = 80 m.

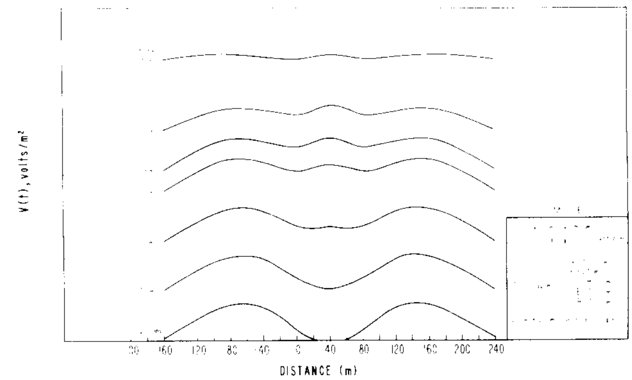

FIGURE 5
Profile of the vertical component of voltage calculated for two prisms in a 1000 Ω.m half-space for a central-loop configuration. The loop dimensions are 25 m by 25 m.

A survey configuration where the source moves along the profile can improve the lateral resolution of the two prisms. For a central-loop configuration, with loops 25 m on a side, both prisms are resolved at 1, 3 and 5 ms, as shown in Fig. 5. The two minima in the profiles indicate the locations of both prisms. At later times interpretational ambiguities could arise because the two separate minima are replaced by a single minimum located half way between the prisms. This single minimum could be interpreted as an isolated conductor. Overall, the shapes of the profiles in Fig. 5 are similar to the scale model results of Ogilvy (1983) for the coincident-loop configuration.

If the half-space response is removed, the time constant estimated from the response of the two prisms at late time is dependent on the type of survey. Unlike the fixed-loop configuration, the time constant varies with position along the profile for the central-loop configuration. When central-loop stations are located away from the two prisms the estimated time constant is the same as in the fixed-loop case: 3.7 ms. However when a central-loop station approaches both prisms the time constant decreases and its smallest value is 2.9 ms at x = 40 m. This variation in the time constant is an indicator of the presence of multiple conductors since the time constant of a single conductor does not vary along the profile.

An important conclusion from our study is the inability of large fixed-loop surveys to resolve multiple conductors. Therefore, when an anomaly is located with this type of survey, we recommend, if possible, further work with a moving source survey because it is more likely to resolve multiple conductors.

Concluding remarks

The usefulness of our TEM solution for high-contrast bodies has been demonstrated with model studies. We investigated 3-D responses under the influence of conductive overburden and we made an evaluation of the resolution of two conductors with different survey configurations. However, our solution is more versatile than we have illustrated, since it is valid for any number of layers and prisms and is designed for many different types of source and receiver configurations. Important exploration problems where it can be applied include, e.g., 3-D airborne TEM model studies and an evaluation of the effect of conductive host on 3-D TEM borehole responses. Finally the solution is not restricted just to TEM applications. Because its basic formulation is in the frequency domain it can be applied easily to frequency-domain exploration problems.

Acknowledgements

We are grateful to U.S. Geological Survey for making the VAX 11/780 computer available for much of this work. We are also indebted to Walt Anderson for his help in installing our program on the VAX computer. Financial support was provided by Amoco Production Co., Arco Oil and Gas Co., Chevron Resources Company, CRA Exploration Pty Ltd, Standard Oil Co., and Unocal Corp., in conjunction with the University of Utah EM Modelling Research Project.

References

Lamontagne, Y., (1975)—'Applications of wideband time-domain electromagnetic measurements in mineral exploration', Ph.D. thesis, Univ. of Toronto.
Nabighian, M. N. (1987)—'Inductive time domain electromagnetic methods', EM mining volume, Society of Exploration Geophysicists, in press.
Newman, G. A. and Hohmann, G. W., (1987)—'Transient electromagnetic responses of high-contrast prisms in a layered earth', Submitted to *Geophysics*.
Ogilvy, R. D., (1983)—'A model study of the transient electromagnetic coincident loop technique', *Geoexploration* **21**, 231–264.