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SCALE-MODEL STUDIES OF THE TX-PARALLEL MODE OF OPERATION FOR FIXED-LOOP ELECTROMAGNETIC PROSPECTING SYSTEMS IN A CONDUCTIVE ENVIRONMENT

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Abstract

Scale-model studies of the Tx-parallel and conventional modes of operation for fixed-loop electromagnetic prospecting systems operating in a conductive environment are compared. The Tx-parallel procedure employs traverses which run parallel to the transmitter, which is laid across the expected trend of target conductors. Emphasis in these studies was placed on the relative contribution of current gathering to the response of conductors.

The Tx-parallel mode of operation was found to provide results which indicated a suppression of the current-gathering effect. This was caused by the close-to-perpendicular orientation of the conductors with respect to the transmitter that is a feature of this mode of operation. This resulted in weaker responses than are provided by the conventional type of survey which promotes the current-gathering effect by virtue of the parallel orientation of the transmitter and conductor used in that mode of operation.

The freedom from the current-gathering effect was found to allow the responses obtained with the Tx-parallel procedure to give a closer representation of the electrical character of target conductors than the responses obtained with the conventional procedure. Conventional responses were found to reflect the electrical character of the host rather than of the target conductor. The Tx-parallel responses were also found to simultaneously locate both edges of a wide conductor, while the conventional procedure indicated that the combined gathered and directly induced currents were located close to the centre of the same conductor, so that its width could not be judged in the conventional data.

A simple numerical modelling method which employs current filaments oriented perpendicular to the traverse to generate a theoretical secondary field which simulates the actual secondary field emitted by a conductor was found to be capable of providing excellent direct matches to the observed data for both types of survey. In cases where the target conductors lay perpendicular to the traverse, the current filaments which produced the matching fields displayed a good agreement with the location and depth of the conductors used in the scale models. However, when the strike of the model conductor deviated from being perpendicular to the traverse, the filament model clearly became physically meaningless despite still being able to provide very good matches to observed data.

Introduction

The Tx-parallel mode of operation for fixed rectangular loop electromagnetic systems in which the receiver moves along traverses parallel to the long side of the transmitter has been examined in several studies. Physical scale-model studies for free-space environments have been described by Bays and Duckworth (1983), Duckworth and Bays (1984) and Duckworth and Cummins (1990). Comparative field tests of the Tx-parallel and conventional modes of operation have been reported for frequency-domain systems by Duckworth and Bays (1984) and Duckworth (1988a). Studies were also done for frequency- and time-domain systems by Pitcher et al. (1983) and Pitcher (1985). The potential of the Tx-parallel mode of operation for the detection of deep conductors was tested by Duckworth and O'Neill (1989a) in a survey which detected a conductor at a depth of 780 m in a 5 ohm-m host environment.

The area of application of the Tx-parallel method which has not previously been covered by a model study is its performance when used in a conductive environment. The present discussion presents physical scale-model studies which relate to that condition.

This study complements a prior study reported by Duckworth and O'Neill (1989b) which detailed the performance of the conventional mode of operation in conductive host environments. The experimental methods and equipment previously described by those authors were employed in this study. These methods will not be again described here.

Characteristics of Conventional and Tx-parallel Surveys

In the conventional mode of operation (Figure 1), where the traverses run perpendicular to the transmitter, every effort is made to ensure that the conductor lies outside the transmitter loop and parallel to that loop. When the rocks underlying the transmitter are conductive, a regional induced current will flow in those rocks as shown in Figure 1. This regional flow will be channelled or gathered by any good conductor that lies parallel to the flow. Thus, the target conductor in Figure 1 will gather

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the regional current. This gathered current will strongly enhance the anomaly recorded over the target conductor, as was shown by Lajoie and West (1976) and Duckworth and O'Neill (1989b).

In the Tx-parallel mode of operation (Figure 2), traverse lines run parallel to the transmitter loop which is laid across the expected trend of the conductor(s), indicated by the regional strike. This means that target conductors will commonly strike almost perpendicular to the transmitter and to the flow of the regional current. Thus, while the regional current must pass through the target conductor, the superior conductive path that the conductor offers will be too short to effect a significant overall reduction in the resistance to the flow of the regional current. Consequently, this configuration will not promote the gathering of current from the host into the target conductor.

Along any Tx-parallel traverse (Figure 2), the anomalous secondary fields are generated by current which flows perpendicular to the transmitter. Regional current flowing through the target conductor will flow parallel to the traverse and will not have a major influence on the anomaly. It will be the locally induced current vortex that will generate the anomaly in this case.

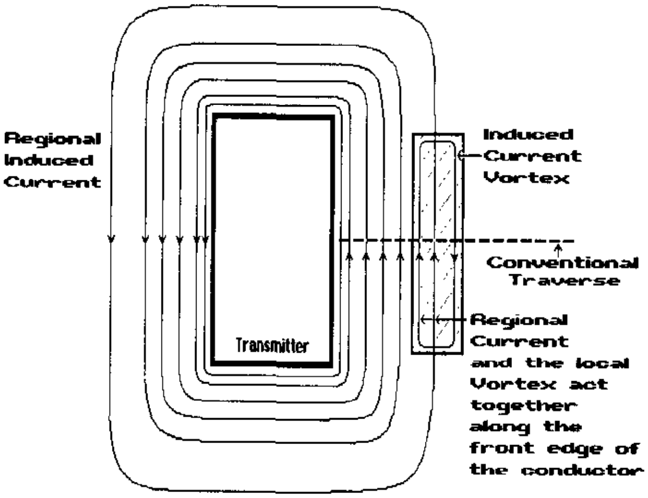

Fig. 1. The conventional survey layout and its relationship to the regional flow of induced current in the host rocks around the transmitter.

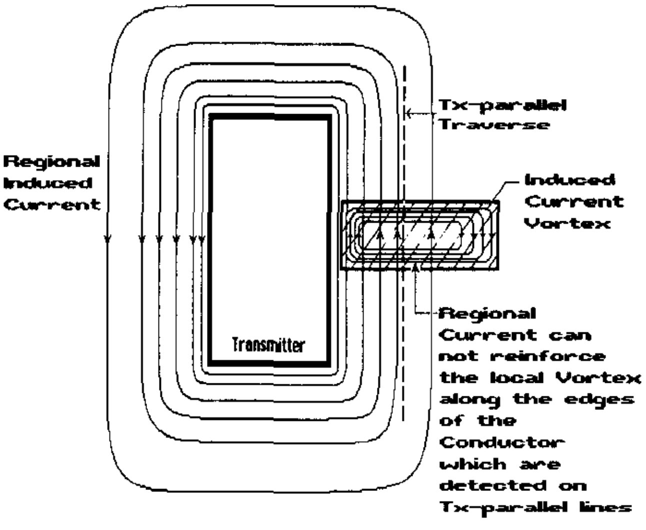

Fig. 2. The configuration of a Tx-parallel survey with respect to the regional current in the host does not promote current gathering.

RESULTS

Figure 3 depicts scale-model profiles published by Duckworth and O'Neill (1989b) for a conventional fixed-loop electromagnetic survey conducted over a vertical tabular conductor of 6.3 x 10^4 S/m conductivity located in a 10 S/m conductive host for model frequencies ranging from 4 kHz to 400 kHz. The corresponding Tx-parallel traverses over the same conductor striking perpendicular to the transmitter at the same depth for the same frequency range and host conductivity are presented in Figure 4. The amplitude and phase profiles presented at the top of each illustration are the actual data recorded over the model. The reduced field strength ratio (RFSR) and phase difference (PD), as used in Turam surveys, were generated numerically from the amplitude and phase profiles. The real and imaginary profiles are the components of the secondary field due to the conductor alone, with the effect of the transmitter field removed.

It should be noted that the plotting scales for RFSR, PD, real and imaginary in Figure 4 have been enhanced. This was done to permit details of the profile geometry to be appreciated. The

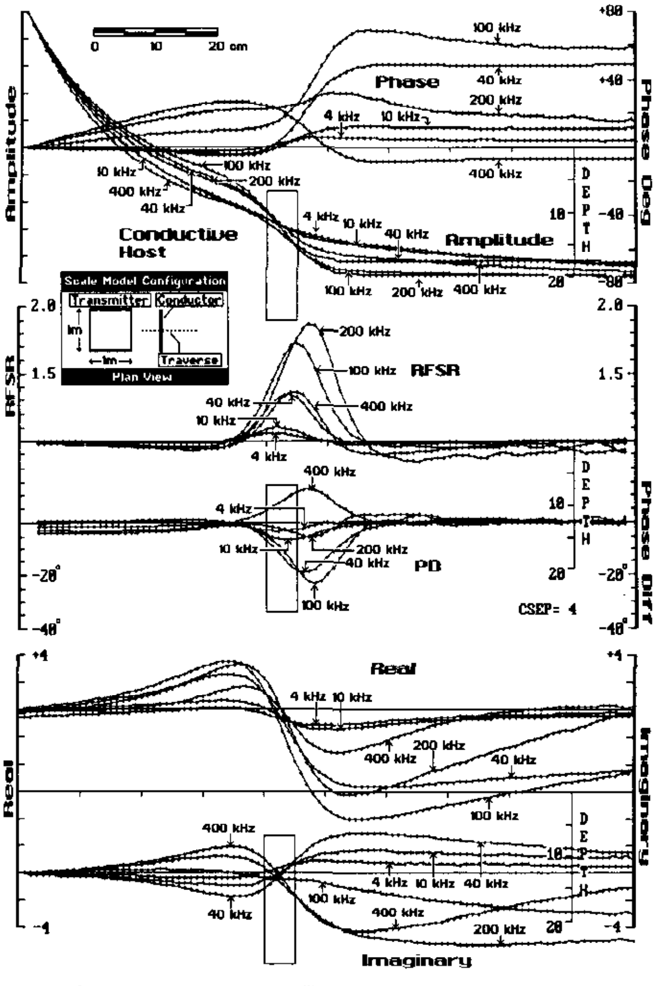

Fig. 3. Conventional survey profiles for a range of model frequencies (after Duckworth and O'Neill, 1989).

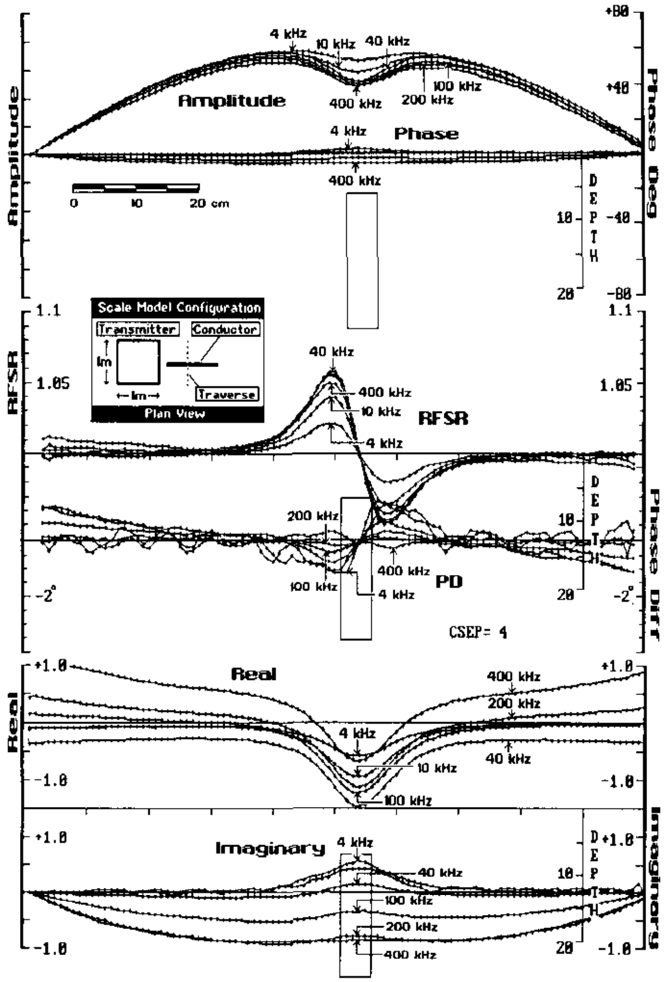

Fig. 4. Tx-parallel profiles over the same conductor that was used for the study depicted in Figure 3.

amplitude data represents the amplified output of the detector coil in arbitrary units. However, the plotting scales for amplitude are identical for all the illustrations presented here, in order that the relative behaviour of the amplitude from case to case may be seen. The units used in plotting the real and imaginary profiles are also arbitrary, but numerical values have been assigned to these plots in order to allow the relative changes of scale between illustrations to be appreciated.

The comparative study of these two modes of operation, which was conducted by Duckworth and Cummins (1990) using free-space conditions, indicated an approximate equality between the responses obtained with the two methods over this same conductor. By comparison, the conductive environment causes the response to be stronger for the conventional survey (Figure 3) than for the Tx-parallel survey (Figure 4). The stronger response for the conventional mode of operation in a conductive environment confirms the expectation discussed above that the conventional type of survey will benefit from the current-gathering effect.

In addition to enhancing the response of a target, the gathered current inverts the phase of the anomaly at high frequencies. This can be seen in the conventional profiles of Figure 3 where the imaginary component of the secondary field shows phase inversion at 100 kHz.

The Tx-parallel phase difference profiles of Figure 4 also show a phase inversion, but this occurs at 400 kHz. In this case the phase inversion results from the phase rotation experienced by the primary field in travelling to the target through the conductive host. There is a corresponding phase rotation experienced by the secondary field emitted by the target as it travels to surface through the conductive host. In this sense, the host acts as a conductive overburden as described by Lowrie and West (1965).

A similar contribution to phase inversion must operate in the conventional configuration but, in that case, the phase of the gathered current within the target conductor provides the dominant effect.

While the enhancement of the response caused by the gathered current in a conventional survey can be viewed as being beneficial, it also causes the anomaly over the conductor to become almost independent of the thickness of the conductor, as was shown by Duckworth and O'Neill (1989b).

By comparison, the relative freedom from the current-gathering effect, which is inherent to the responses seen in a Tx-parallel survey means that those responses will be more representative of the conductance of the target.

The intuitive view that a conductor oriented approximately perpendicular to the transmitter will not couple with the transmitter ignores geological reality. Physical modelling and several field surveys, which have been referred to earlier, have shown that it is difficult to achieve the decoupling of vertically dipping thin conductors, because even minor deviations from perpendicular strike produce significant coupling. In addition, cases where dip is less than vertical or the conductor displays appreciable thickness, cause the coupling to become very effective.

NUMERICAL MODELLING

Two-dimensional theoretical methods are inherently incapable of treating the current-gathering effect and they cannot model the flow of current perpendicular to the transmitter. Thus, any modelling of the current-gathering effect or of the responses generated by a Tx-parallel survey must be based on a three-dimensional theoretical representation of the conductivity distribution around the transmitter loop, or upon physical scale modelling, as was used in this study.

The severe computational demands of three-dimensional theoretical modelling are unsuited to the iterative matching of theoretical to observed data. However, for the explorationist who can not justify the cost of three-dimensional numerical modelling, a low-cost alternative lies in the current-filament (or line-current) modelling method (Duckworth, 1972). This modelling method can be implemented on any personal computer and can produce satisfactory matches to observed data obtained with either conventional or Tx-parallel surveys. The current-filament model (where the filaments are assumed to be located in free-space) permits the computation of a theoretical field distribution which simulates the magnetic field due to the actual induced current concentrations in the conductor. This model was shown by Duckworth and O'Neill (1989b) to be capable of providing very close matches to observed data even if those data are phase-inverted. The locations of the filaments, once a match has been achieved, correspond very well to the spatial location of the target conductor.

In order to provide an additional basis for discussion of the scale-model results and to demonstrate that the filament model is a very effective interpretation tool, it was applied to the simulation and matching of the scale-model data acquired in this study. The results of this matching to scale-model data acquired at 40 kHz for both the conventional and Tx-parallel data are presented in Figures 5, 6 and 7. In these figures the solid profiles are the theoretical profiles generated by the filament model while the discrete data points were recorded by the scale-model system. The fine dotted profiles are the recorded primary field with the target conductor removed.

Figure 5 depicts the scale-model conventional profiles for 40 kHz from Figure 3. At this model frequency, the response was strongly enhanced by current gathering and close to phase inversion as can be seen in Figure 3. The filament model match to the scale-model data in Figure 5 is remarkably complete, considering the simplicity of the model on which it is based.

The corresponding Tx-parallel profile over the same conductor along with the filament model matching profile are shown in Figure 6.

In the conventional profile of Figure 5, the match to the observed scale-model data required only two current filaments. These currents are the real and imaginary components of what can be viewed as a single current concentration. The difference in the spatial location of these components of the induced current is necessary in order to achieve a match to the observed data, as discussed by Duckworth (1988b). The location of these components of this current filament close to the centre of the actual conductor shows that this simple interpretation method would have provided a reliable drilling target in this case.

In low-frequency (4 kHz) tests of the conventional mode of operation over this same conductor, Duckworth and O'Neill (1989b) found that the filament model required currents close to the bottom of the conductor in order to achieve a match to the scale-model profiles. These deep currents provided a measure of the depth extent of the target. However, at 40 kHz with a strong current-gathering effect in operation, the effects of deeper currents were lost. This is shown by the lack of need for deep currents in the match achieved in Figure 5.

In the case of the Tx-parallel profile of Figure 6 the matching filament model required 4 separate current filaments to achieve

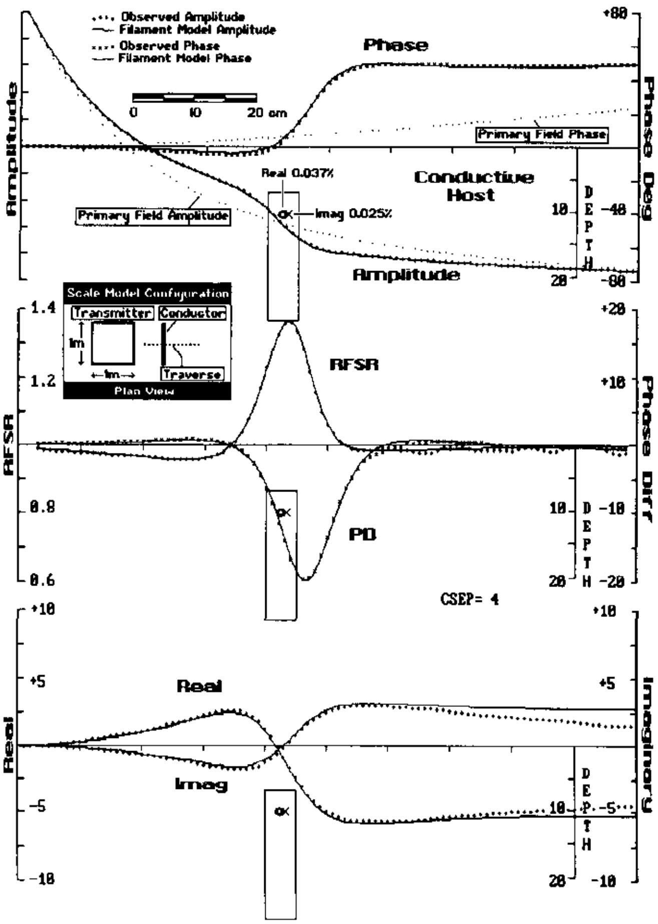

Fig. 5. Scale-model and matched theoretical profiles for the 40-kHz profile illustrated in Figure 3.

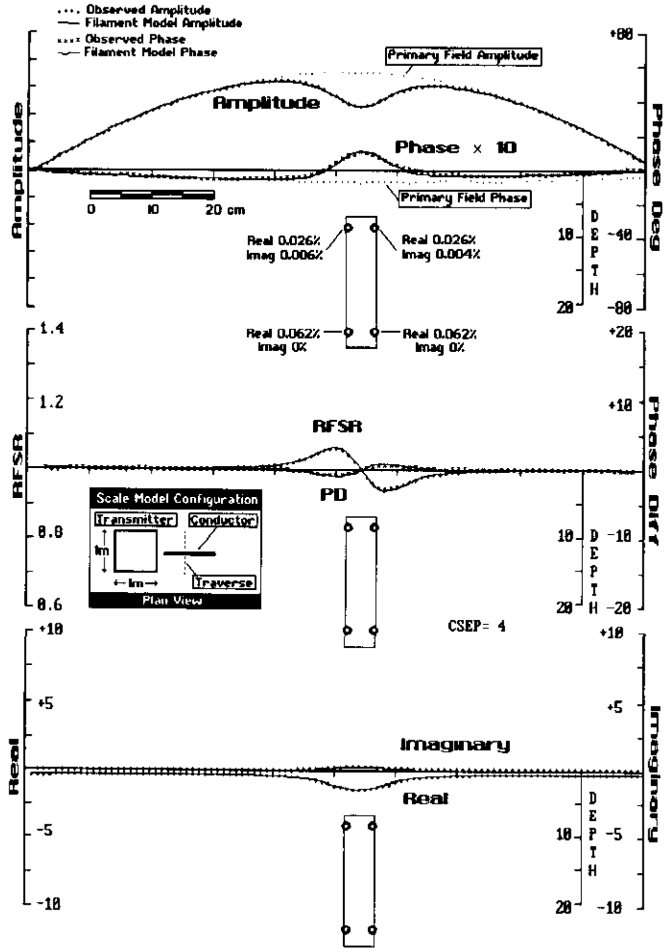

Fig. 6. Scale-model and matched theoretical profiles for the 40-kHz Tx-parallel profile from Figure 4.

a satisfactory match (it should be noted that the phase profile was magnified by 10 to allow the features of the profile to be appreciated). The two currents located close to the top of the conductor can be regarded as being related to the two sides of the local vortex of current which must have existed close to the top face of the conductor, as in Figure 2. However, it is essential that the currents used in the filament model should not be regarded as exact representations of the actual currents which existed in the conductor. It was not found to be necessary to spatially separate the real and imaginary components of these currents as was the case in Figure 5.

The magnitudes of the real and imaginary components of the shallow currents in Figure 6 show a ratio of 4:1. In free-space profiles (not shown) this ratio became 8:1 at the same frequency, thereby indicating a response close to the inductive limit. This ratio of 4:1 is better related to the character of the excellent conductor that this slab of graphite represented, compared to the 1.48:1 ratio displayed by the current components in Figure 5. This confirms the earlier suggestion that the results from a Tx-parallel survey in a conductive environment would be more closely related to the quality of the target conductor than would conventional survey data.

It is notable that in Figure 6 the current filament interpretation of the Tx-parallel responses defines the location of both edges of the conductor. By comparison, the conventional profiles of Figure 5 do not permit either the front or back edge of the conductor to be located, because the matching filaments lie at the centre of the conductor.

The deeper pair of currents in Figure 6 can be viewed as being related to the current vortex in the bottom surface of the conductor, but they present an apparent paradox because they are much stronger than the shallow currents. It must be remembered that these currents are the currents that in a free-space environment produce a secondary field along the profile which merely simulates the actual detected field due to a target in a conductive host. The magnitudes and phases of these simulating filaments of current do not have to match the magnitudes and phases of the actual currents which flowed in the conductor. However, it does appear that they do provide a reasonable approximation to the true spatial location of the induced currents, and thereby provide a measure of the depth extent of the conductor. This contrasts with the apparent lack of any depth extent information in the conventional profiles of Figure 5, where the shallow current match could not be improved by including any deep currents in that model.

This application of the filament model to Tx-parallel data indicates that this simple model would have provided a reliable indication of the position of this conductor for drilling purposes, just as it did for the conventional data.

The magnitudes (as a percentage of transmitter current) of the current filaments used to match the conventional and Tx-parallel profiles were 0.046% and 0.030%, respectively. This confirms the qualitative impression of the overall stronger response in the conventional configuration due to the gathered current. However, it is surprising that the current indicated for the Tx-parallel case is not as weak as might be expected. The relatively strong response provided by the Tx-parallel mode of operation comes from being able to work closer to the transmitter than is possible in the conventional type of survey.

In the conventional type of survey, the transmitter must be sufficiently displaced from the location of the target to allow full development of the anomaly along the traverse. The deeper the target, the greater must be this displacement because of the increasing width of the anomaly. This necessary displacement causes the transmitter-to-target coupling to be decreased for deeper targets, yet this clearly conflicts with the need to maximize the coupling to deeper conductors.

The Tx-parallel mode of operation does not suffer from this conflict. It allows any length of traverse at any desired separation from the transmitter. It also allows the transmitter to be placed directly over the target no matter what the depth of that target. This places the transmitter as close to the conductor as possible, thereby compensating for the disadvantage that the Tx-parallel configuration suffers due to reduced primary coupling and lack of current gathering.

While the filament model can provide very effective interpretation of the location of the target it can also produce results which can be misleading. Figure 7 illustrates a case in which the filament model was again very successful at achieving a

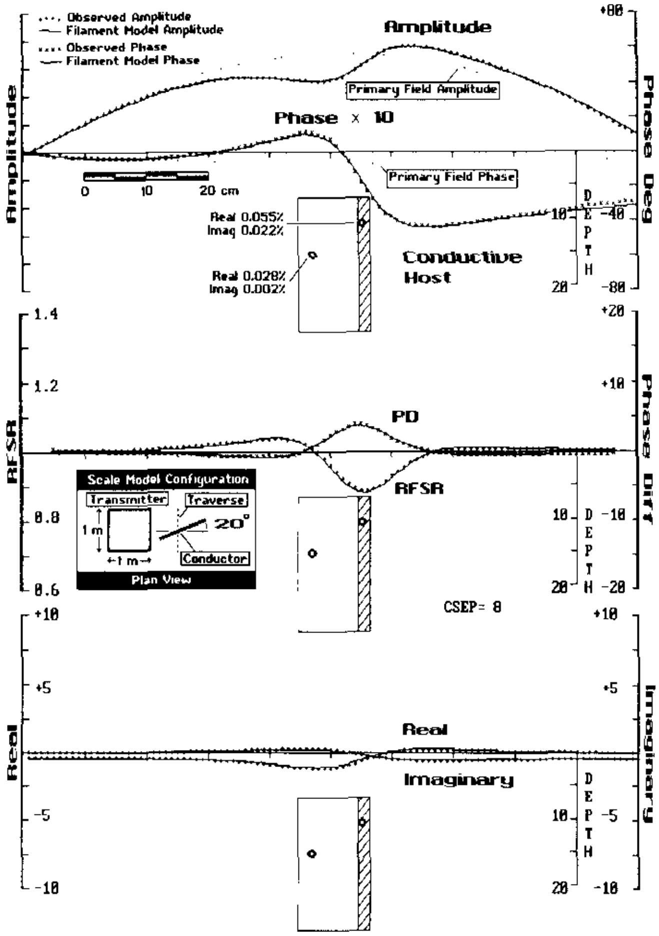

Fig. 7. Tx-parallel results for a conductor striking at 70 degrees to the traverse. The matching current-filament model is physically unrelated to the actual current flow in the conductor.

match to the observed profiles, but the filament model and the actual current induced into the conductor were completely unrelated. In this case, the strike of the conductor was not perpendicular to the transmitter, yet the simulating filaments are perpendicular to the transmitter. The pair of currents which were used to match the observed profile could equally well simulate the response of a conductor dipping at approximately 45 degrees. This demonstrates again that the currents used in the filament model do not have to be directly related to actual currents in the conductor. It is essential that any individual current filament be regarded as no more than a possible representation of the current that actually existed in the conductor.

The example in Figure 7 also shows that deviations of the target conductor from perpendicular strike result in Tx-parallel responses which can be mistaken for those of a conductor dipping at less than 90 degrees. Explanations of this effect were provided by Cummins (1986). This misinterpretation can be immediately recognized if more than one traverse at increasing separation from the transmitter is conducted.

DISCUSSION

The intent of this paper is to provide a brief comparison of the main features of the conventional and Tx-parallel modes of operation for Turam and other fixed-loop systems. Comprehensive comparisons, and extensive suites of model responses, for both the conventional and Tx-parallel modes of operation are available in the work of Cummins (1986) and O'Neill (1989).

Most notable in the comparison of these two methods is the benefit in anomaly magnitude that the conventional procedure is able to gain from current gathering. The Tx-parallel procedure suppresses this effect, but this suppression can be of benefit in some circumstances. For instance, the lack of current-gathering effects in Tx-parallel responses permits the results to be better related to the electrical character of the target conductor than are responses obtained in a conventional survey. Conventionally acquired responses tend to reflect the electrical character of the host rather than of the target.

An additional benefit that the Tx-parallel method appears to offer is its ability to simultaneously locate both edges of a wide conductor, and to indicate its depth extent, even in a conductive environment.

The Tx-parallel mode of operation has the considerable advantage of being able to allow the fixed-loop transmitter to be used in a reconnaissance role as was shown by Duckworth (1988a). The conventional mode of operation can only achieve its advantage in anomaly magnitude if the position and alignment of the target are known, in order that the correct placing of the transmitter can be achieved. If it is necessary to know the location and strike of a target before conducting a conventional fixed-loop type of survey then there appears to be little point in conducting that survey; it would be redundant. The Tx-parallel type of survey does not require such prior information. The transmitter can be laid across the regional strike trend as indicated by outcrop. It is possible that a conductor could lie perpendicular to the dominant trend in an area and therefore might be missed by a Tx-parallel survey, but the probability of achieving this misorientation appears to be small.

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