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THE RESPONSE OF A COINCIDENT–COIL ELECTROMAGNETIC PROSPECTING SYSTEM TO TARGETS LOCATED BELOW CONDUCTIVE OVERBURDEN

K. DUCKWORTH[1]

ABSTRACT

Comparison of the performance of a coincident-coil frequency-domain electromagnetic exploration system with the performance of the same coils employed in the standard horizontal coplanar separated-coil configuration was conducted by means of physical scale modelling. The particular aim of this study was to examine the potential exploration benefits of the coincident-coil system with reference to this well-known standard horizontal coplanar coil system when both coil configurations are applied to the detection of targets located below highly conductive overburden. Responses were obtained with and without overburden over targets consisting of single and multiple tabular vertically dipping conductors and a spherical conductor. In all cases, the responses obtained demonstrated that while the coincident-coil system produces stronger responses to the conductive overburden than do separated coils, the response of this system to targets located below a conductive overburden (when the response of the overburden is removed) is less affected by the overburden than is the response when the coils are separated. This low sensitivity to the effect of an overburden on the anomalous field of targets below that overburden indicates that for the frequency range normally employed in mineral exploration and for the types of overburden normally encountered, the interpretation of the responses of target conductors obtained with the coincident-coil system can be based on methods developed for targets located in free space. Comparison of the model data with published field surveys indicates that this low sensitivity to the effect of conductive overburden on the response of targets located below that overburden will be valid for exploration frequencies up to 2000 Hz even in circumstances where the overburden will invert the phase response of a conventional horizontal coplanar-coil system.

INTRODUCTION

The response of electromagnetic prospecting systems to conductive mineral targets when those targets are located below conductive overburden has been described by a number of authors (e.g., Lowrie and West, 1965; Lajoie and West, 1976; Hanneson and West, 1984). A feature common to all of these studies is the demonstration of strong phase rotation and attenuation of the signal received from the target conductors when the targets are located in a free-space environment below a conductive overburden. These effects have been shown to be progressively enhanced by increases of overburden thickness or conductivity and by increase of the operating frequency. In the case of moving source electromagnetic systems, it is also found that increasing the transmitter-to-receiver separation increases the phase rotation and attenuation of the field received from the target conductor.

These effects are due to the phase rotation and attenuation of the primary and secondary fields as they are propagated to and from the target through the overburden. The longer the path for these signals within the overburden the stronger these effects will be. Thus, it is to be expected that a thicker overburden will enhance these effects and that increased separation between the coils will increase this length of path and thereby also increase the effect of the overburden.

As these effects are in no way beneficial to the detection of such targets it appears desirable to minimize the length of path that signals must follow within the overburden. In this context, the coincident-coil configuration offers a notable advantage. This may be appreciated by consideration of Figure 1 where the coincident-coil system is depicted as employing separate transmitter and receiver coils rigidly mounted in a zero-coupled configuration at a separation small enough for the coils to be considered to be coincident as described by Duckworth et al. (1993). When the transient or time-domain mode of operation is employed, the coincident-coil concept can be implemented with a single, large, nonrigid air-cored loop for both transmission and reception (Velikin and Bulgakov, 1967). In the frequency-domain device described by Duckworth et al. (1993) the requirement of zero coupling can only be implemented with small, rigid, dipole-type coils permanently clamped into a single frame that permits the coils to be easily operated with both coil planes vertical as shown in Figure 1. This orientation allows both coils to achieve simultaneous maximum coupling with a steeply dipping tabular conductor when both coils are located directly above and coplanar with the target. The horizontal coplanar separated-coil configuration achieves its peak response to a steeply dipping tabular target when the coils are equidistant from the target with the target between the coils as shown in Figure 1. Clearly, the vertical coincident

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[1]Department of Geology and Geophysics, The University of Calgary, Calgary, Alberta T2N 1N4

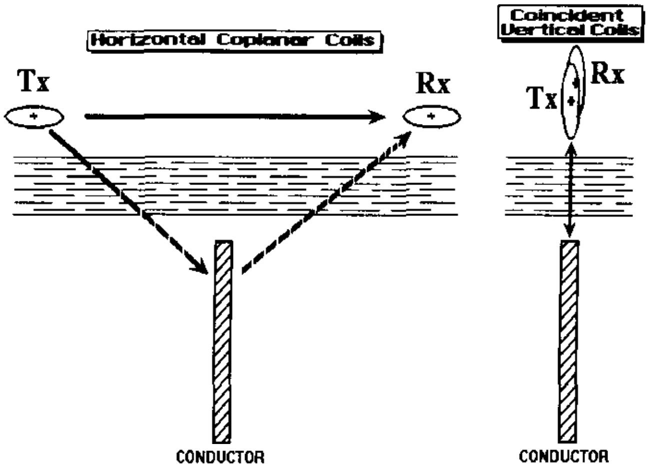

Fig. 1. The electromagnetic field propagated through an overburden to a target conductor and the field propagated back to the receiver by the target experience longer paths within the overburden if the coils are separated than if the coils are coincident. This would apply regardless of the orientation of the coils. This minimum path length provided by the coincident-coil system indicates that the coincident-coil responses to targets located below an overburden will be less affected by the overburden than will the responses detected by separated horizontal coplanar coils (or any separated coil configuration) over the same target.

coils located directly over the target provide the shortest possible path within the overburden for the fields propagating to and from the target so that it might be expected that the response of the target to a coincident-coil system (after the removal of the response of the overburden) would show significantly less phase rotation and attenuation than the response to that same target provided by a separated horizontal-coil system. This potential benefit, combined with the fact that at peak response the coincident coils are inevitably much more strongly coupled to the target than the separated horizontal coplanar coils (Duckworth et al., 1993), suggests that the coincident-coil configuration can be notably effective in the search for targets located below conductive overburden.

The argument of minimum path length would also apply to horizontal coincident coils except that the peak anomaly for horizontal coincident coils will occur with the coils located to the side of the conductor by a distance equal to 0.82 times the depth of the conductor (Duckworth et al., 1993), so that for horizontal coincident coils the path length in the overburden will be 1.29 times larger than that for vertical coils. If full advantage is to be taken of the coincident-coil concept then the coils should normally be operated in the vertical configuration, particularly as it produces a notably simpler single-peaked form of anomaly than the double-peaked form provided by the horizontal configuration (Duckworth et al., 1993). The comparison of the vertical coincident configuration with the familiar horizontal coplanar separated-coil configuration provides the potential user who is interested in operating EM systems on the ground with a view of the full merit of the coincident-coil device as it will be used.

It must be stressed that the coincident-coil configuration derives its ability to minimize the effects of an overburden (i.e., the effect on the anomaly due to a target located below that overburden) from the minimization of the path length within the overburden. This benefit will be greatest when the coincident coils are vertical but the horizontal configuration of the coincident coils provides a path length for peak anomaly which is only 29% greater than that provided by the vertical coils. This is still significantly better than the path length provided by separated coils which for a typical depth-to-coil separation ratio of 0.25 would give a path length 2.24 times greater than the vertical coincident-coil path length, i.e., a path length greater by 124%. This would improve to being only 41% greater if the depth-to-coil separation ratio was increased to 0.5, but at this ratio the target would be marginally detectable in responses presented as a percentage of the primary coupling.

The fact that vertical coils offer lower sensitivity to the overburden itself than do horizontal coils is an incidental benefit which results in the baseline shifts due to the overburden being smaller than those that would be found with horizontal coils. It may be noted that separated vertical coils would offer no advantages over separated horizontal coils in terms of the path length within the overburden.

This lower sensitivity to the overburden for the vertical coincident coils indicates that geologic noise due to variations in the thickness or conductivity of an overburden will be less significant in vertical coincident-coil responses than in responses obtained with horizontal coincident coils. In addition, the 0.82D offset (where D is target depth) from the target at peak anomaly for horizontal coils and the perpendicular orientation of the coils with respect to the plane of a vertical target causes the anomaly magnitudes provided by horizontal coincident coils to be significantly weaker than those provided by vertical coincident coils which at peak anomaly are coplanar with and closer to the vertical target. Thus, the horizontal coincident-coil responses will display poorer signal-to-noise ratio than will the vertical coincident-coil responses.

The horizontal coincident-coil configuration will only be used in the field to determine the depth and dip of a target (Duckworth et al., 1993). In this application, the geometry of the double-peaked type of anomaly provided by the horizontal coincident coils displays a high sensitivity to both depth and dip variations. The single-peak type of anomaly provided by the vertical coils is very insensitive to dip and, while the width of this peak could be used as a depth indicator, it would be inferior for this purpose to the type of anomaly provided by the horizontal coils. The vertical coil response will be clearly superior in the initial detection and spatial resolution of target responses. Thus, as the vertical coil configuration will be the one used in reconnaissance exploration it is the performance of that configuration which is of greatest interest in terms of demonstrating the potential exploration advantages of the coincident-coil system. A comparison of the horizontal coincident coils with the standard horizontal separated coils would not demonstrate the full advantage that the coincident-coil system can offer.

A comparison of vertical coincident coils with vertical separated coils would be of little value as separated vertical coil systems have seen only limited use in ground-borne systems in mineral exploration (although widely used in environmental monitoring). It is a specific aim of the coincident-coil system that it provide the operator on the ground with a new approach to the detection of mineral targets which goes beyond what the widely used conventional horizontal coplanar-coil configuration offers.

The following physical modelling results demonstrate that the responses provided by a coincident-coil system do indeed show significantly less overburden-generated phase rotation and attenuation of the target anomaly than is shown by the horizontal coplanar separated-coil system.

MODELLING RESULTS

In order to demonstrate the effect of a conductive overburden, the responses of target conductors are presented first for the case where no overburden was present, as shown in Figures 2 and 3. The response of the coincident vertical coils is displayed in Figure 2 while Figure 3 displays the response of the same coils in a separated horizontal coplanar configuration (separation 20 cm). In both cases the coils were traversed over the same group of closely spaced vertical tabular conductors of effectively infinite depth and strike extent which were located at a depth equal to the separation between the conductors which was 0.15 times the coplanar-coil separation. In the context of a field survey conducted with a horizontal coplanar-coil separation of 200 m, this target depth would be 30 m (a linear scale factor of 1000:1). A smaller separation of the horizontal coplanar coils would cause the output of that system to provide better spatial resolution of the anomalies. However, as the width of the anomaly due to a single target is equal to the coil separation regardless of the depth of that target, the complete separation of the anomalies of closely spaced targets requires that the separation of those targets approach or exceed the separation of the coils (Gupta et al., 1988). Thus, for the targets employed in this study the coil separation would have had to be reduced to 3 cm in the model or the equivalent 30 m full scale. This would have resulted in a depth-to-separation ratio of 1.0 which is considerably larger than the ratio at which it is practical to detect targets except in rigid beam EM systems.

A basis for magnitude comparisons between the two coil configurations was established by relating all output voltages from the receiver coil to the output voltage of that same coil when the coils were coplanar and separated by 20 cm in free space. As the coincident coils were zero coupled, their output in nonanomalous conditions was zero, so that their response could not be referenced to their output in such conditions. The choice of a 20-cm coil separation for comparison purposes was dictated by the practical consideration of coil clearance with respect to the models, but any other separation could have been used with the same results if appropriate adjustment of target depth and conductivity to maintain scaling invariance had been employed. The results presented here are entirely equivalent to presenting full-scale coincident-coil responses as percentages of the primary field detected by the same coils reconfigured to be horizontal and coplanar at a separation of 200 m.

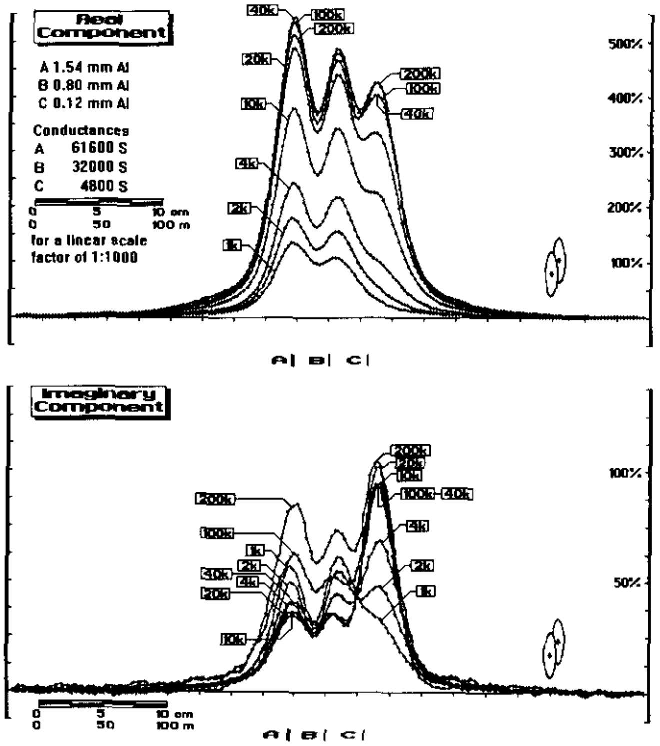

Fig. 2. Coincident vertical coil responses over three vertical tabular conductors located at a depth equal to their separation of 3 cm (equivalent to a full-scale depth of 30 m for the scale relationship discussed in the text). It is notable that the imaginary component response of the weak conductor C increased throughout the frequency range while the imaginary component responses of the two good conductors declined from 1 to 20 kHz then rose from 20 to 200 kHz due to the influence of conductor C. The presence and relative quality of all three conductors are clearly represented.

It should be noted that the vertical scale in Figure 2b has been magnified in order to make it possible to see and discuss the behaviour of the imaginary component of the response. It should also be noted that the vertical scale of the responses presented in Figure 3 for the horizontal coplanar coils have been magnified by a factor of approximately 5 with respect to the scales used for the real component profiles for the coincident coils in Figure 2a.

This method of relating the magnitudes of the responses very clearly demonstrates that the secondary fields detected by the coincident vertical coils at peak anomaly were notably stronger than were those detected by the same coils in the horizontal coplanar configuration. For example, the horizontal coplanar-coil responses of Figure 3 indicate that at the 2 kHz model frequency the anomaly magnitudes over the good conductors were 45% real component and 4% imaginary component, which corresponds to a dimensionless response parameter with a magnitude of 303 from the anomaly index diagram published by Duckworth et al. (1993, their figure 2) with the response parameter defined as:

$$\alpha = \sigma t \mu \omega L$$

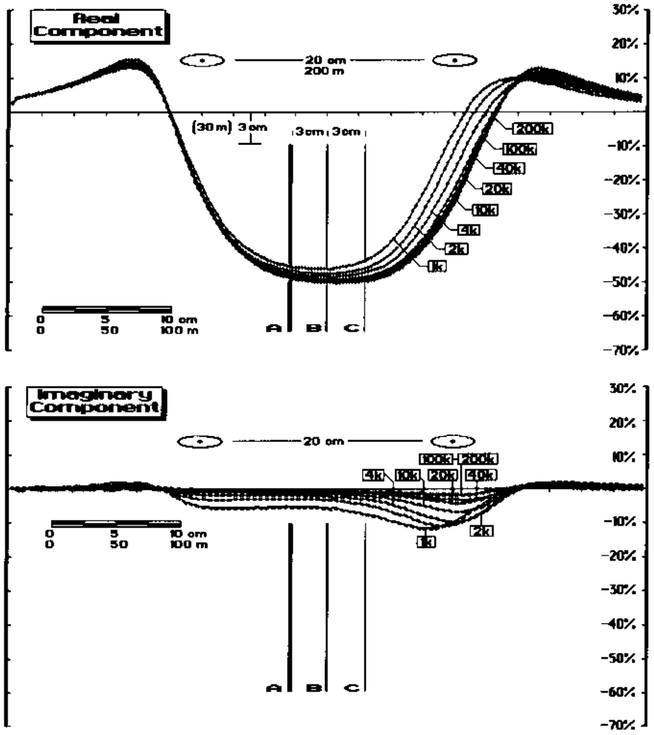

Fig. 3. Horizontal coplanar-coil responses obtained over the same targets shown in Figure 2 with the same coils used in the coincident configuration. The presence of the three separate conductors can not be recognized in these profiles other than in the widening of the anomaly as conductor C became more responsive at higher frequencies.

where σt is the target conductance, ω is the angular frequency, and L is the coil separation.

For a full-scale coil system with a separation of $L = 200$ m (a linear scale factor of 1000:1) and a transmitter frequency of 2 kHz (note that the frequency in the model and full scale are the same) this response parameter indicates that this response would be detected over a full-scale target with a conductance of 96 S. As this 96 S full-scale conductance relates to the combined response of conductors A, B and C it can be inferred that, individually, these conductors represent full-scale conductances less than 96 S. In fact, conductor A will represent a full-scale conductor of approximately 60 S conductance, conductor B, 31 S and conductor C, 5 S. The measured thicknesses of the model conductors and the conductivity of the metal show the actual conductances of the models as A, 61 600 S, B, 32 000 S and C, 4800 S which for a scale factor of 1000:1 represent 61.6 S, 32 S and 4.8 S full scale. The coincident-coil anomaly in Figure 2 over conductor A for a model frequency of 2 kHz was 180% real component and 50% imaginary component, and it can be expected that for a 1000:1 scale factor this would be the anomaly that the coincident-coil system would detect over a full-scale conductor of 60 S conductance with a depth of 30 m for the same transmitter frequency of 2 kHz. Thus, in the full-scale system, this 60 S target would produce a real-component response to the coincident coils at 2 kHz which would be 4 times stronger (180%/45%) and an imaginary-component response 12 times stronger (50%/4%) than the response produced by the separated horizontal coplanar coils, which would have the benefit of responding to the conductors in a group as though they were a stronger single conductor of 96 S conductance.

For an increase of the model frequency to 20 kHz the coincident-coil anomaly over conductor A would be 500% real component and 30% imaginary while the separated-coil anomaly in Figure 3 would be 50% real and 2% imaginary, so that the response would, in this case, be even more notably in favour of the coincident-coil system with an advantage of 10:1 in the real component. For the scale factor of 1000:1 used here and with the frequency the same in the model and full scale, the results presented in Figure 2 represent what would be seen in the response of conductors of 60 S, 31 S and 5 S for the same frequencies full scale. The high end of this frequency range (up to 50 kHz) is becoming more frequently used in actual full-scale exploration but even at the low end of the range the coincident-coil responses are significantly stronger than the separated-coil responses. Thus, it appears reasonable to predict that coincident coils will produce notably stronger responses from targets than can the same coils used in a separated configuration throughout the frequency range used in mineral exploration.

It is a particular feature of the coincident-coil device that its response does not approach the inductive limit until the target conductance or the transmitter frequency has reached much higher values than those which cause inductive limit behaviour in the separated-coil system (Duckworth et al., 1993). This effect as it relates to frequency can be seen in Figures 2 and 3 because the separated-coil response over the conductors in free space (Figure 3) was already almost at the inductive limit over conductors A and B at 4 kHz, while the coincident-coil anomaly continued to develop and only reached this limit at 40 kHz.

If the inductive limit was approached by increasing the conductance of the target at fixed frequency, the separated-coil response would reach the inductive limit for lower conductance than would the coincident-coil response. This is also demonstrated by Figures 2 and 3 because the conductance of the three targets varies over a wide range. However, the merging of the three anomalies in Figure 3 does not permit this to be seen as clearly for the separated-coil response as it is for the coincident-coil response of Figure 2. Thus, over very high conductance targets, the response provided by the coincident coils may approach the much stronger responses seen at high frequencies in Figure 2, while over these same high conductance targets the separated-coil responses will be insensitive to the conductance and unable to discriminate between the targets on the basis of conductance.

This tendency for the separated-coil system to display inductive limit behaviour at much lower frequency than the coincident-coil system suggests that the use of higher frequencies in a separated-coil system does not provide any advantage for the separated-coil system as the responses will quickly become unchanging with increase of frequency. Larger separations will, of course, only cause inductive limit behaviour to be observed at lower frequencies. However, it was shown by Duckworth et al. (1993) that the separated-coil system can outperform the coincident-coil system in discriminating between low conductance targets.

For shallower targets the response of the coincident coils will increase very rapidly without limit while the separated-coil response can increase by no more than 10% from the magnitudes displayed in Figure 3, so that for shallower targets the relative strength of the coincident-coil response will be greater even than the figures shown here. For example, in model results published by Duckworth et al. (1993) for a depth-to-separation ratio of 0.1 (target depth to separation of the horizontal coplanar coils) over a high-conductance target, the coincident-coil real response over the same target at the same depth was found to be approximately 20 times stronger than the separated-coil response and that for truly coincident coils perfect conductor theory indicated that the ratio should be 52:1 for that depth-to-separation ratio. The relatively weaker response provided by the scale-model system was due to the fact that the size of the model coils made it necessary to separate them axially and radially by distances which did not allow them to be placed at the minimum distance from the target that true coincidence would allow.

Increasing the separation of the horizontal coplanar coils while leaving the target at the same depth would increase the real component but by no more than 10% from the values shown in Figure 3, yet this would cause the primary coupling to become very much weaker, and it would also cause the detected secondary fields to become much weaker. In that the secondary fields detected by the coincident coils would be unchanged in such circumstances, the anomalies that the coincident coils provide can only get stronger in relation to the separated-coil anomalies for larger separations.

Reducing the separation of the horizontal coplanar coils for a fixed target depth would reduce the relative advantage provided by the coincident-coil system because the reference coupling would be much stronger, and the secondary fields detected by the two systems would become comparable in magnitude. Thus, for very large depth-to-separation ratios the responses provided by the two systems would be comparable in magnitude. However, for any depth-to-separation ratio, the vertical coincident coils will inevitably be more strongly coupled to steeply dipping tabular targets than the horizontal coplanar separated coils.

As shown in Figures 2 and 3, a selection of 8 frequencies ranging from 1 kHz to 200 kHz was employed in the model. The three conductors were aluminum sheet of widely differing conductance, with conductor A having a model conductance of 61 600 S (61.6 S full scale for a 1000:1 scale factor), conductor B 32 000 S (32 S) and conductor C, the weakest, with a model conductance of 4800 S (4.8 S). The relative conductance of the three conductors is readily appreciated in the coincident-coil response profiles of Figure 2a where it is notable that the poor conductor C showed almost no real component response at the lowest frequencies. The imaginary component responses of Figure 2b also reflect the relative conductance of the three conductors but with some complication due to the mutual interaction of the conductors. This is seen in the decline of the imaginary response of conductors A and B from 1 to 20 kHz followed by an unexpected rise in their response from 20 to 200 kHz. This rise appears to be due to what can be described as a pull-up caused by the influence of the strong imaginary component response of conductor C which increased from 1 to 200 kHz. It appears reasonable to expect that in the absence of conductor C, the imaginary responses of both conductors A and B would have declined progressively for increasing frequency. This was not tested directly as this pull-up effect was not recognized until the imaginary component responses of Figure 2 were plotted with the magnified scale used in that figure. There is clearly a need for additional work to be done on these effects.

The responses of the three conductors as recorded by the same coils in a separated horizontal coplanar configuration (Figure 3) provide only subtle indications of the presence of three separate conductors and suggest that even if the separate presence of the very good conductors A and B was recognized they would be seen as having identical and very high conductance. Conductor C is indicated only by its increasing effect on the width of the real anomaly (Figure 3a) for higher frequencies and by its effect on the imaginary component (Figure 3b) to the right of the centre of the anomaly.

The effect of a sheet of overburden of 480 S (0.48 S) conductance on the response of the three conductors as detected by vertical coincident coils is shown in Figure 4. This conductance is the smallest available when using metal foil as the model material. As discussed later, this overburden conductance results in responses that are significantly stronger than what may be expected in actual full-scale exploration but it provides a very effective test of the premise of this study that the anomalous response of targets detected by a coincident-coil configuration will be less affected by such an overburden than will the responses provided by separated coils. In presenting the profiles shown in Figures 4 and 5 the baseline shifts due to the presence of the overburden have been removed. These baseline shifts are shown later to be large, but the intention here is to describe the effects of the overburden upon the anomalous secondary fields from the target conductors alone. Comparison of the real component profiles of Figure 4a with those of Figure 2a shows that the magnitude of the anomalous response for the three target conductors was almost unchanged from 1 to 4 kHz and only slightly attenuated at 10 kHz. At 20 kHz a strong attenuation was evident but this was in part an artifact of phase rotation which was also increasing strongly. This rotation can be appreciated because the real component response of the three conductors becomes inverted at 100 kHz in Figure 4a but anomalies due to the three separate conductors are clearly identifiable even at 200 kHz.

The corresponding imaginary component profiles with the overburden in place shown in Figure 4b provide a clear indication of the phase rotation and of the phase inversion which occurs at different frequencies for the three conductors. For conductor A phase inversion occurred at 4 kHz while for

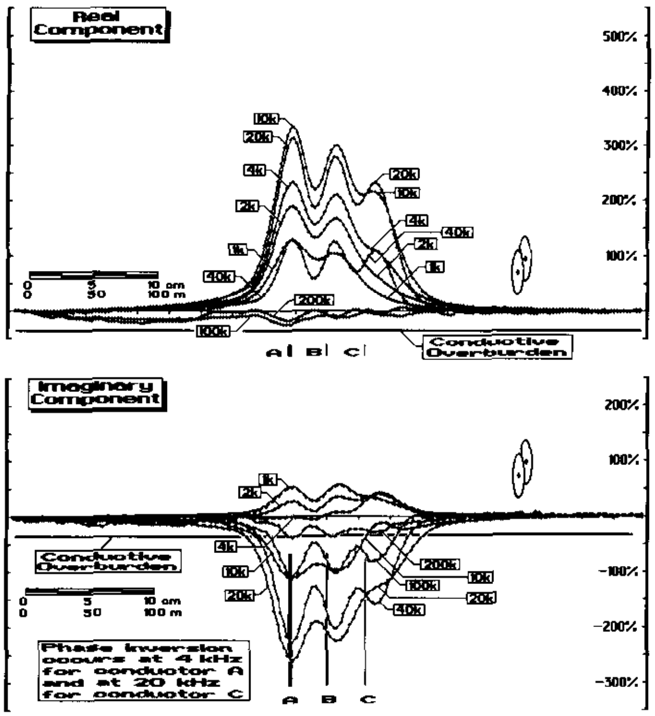

Fig. 4. Placing a 480 S overburden between the coincident vertical coils and the target produced little effect in the real component up to 10 kHz. The imaginary component indicated that phase inversion occurred for the good conductors A and B at approximately 4 kHz but occurred for the weak conductor C between 10 and 20 kHz. The presence and relative conductance of the targets was clearly represented at all frequencies even after the real component became inverted. The strong conductors cause lateral displacement of the anomaly of the weak conductor. Baseline displacements have been removed.

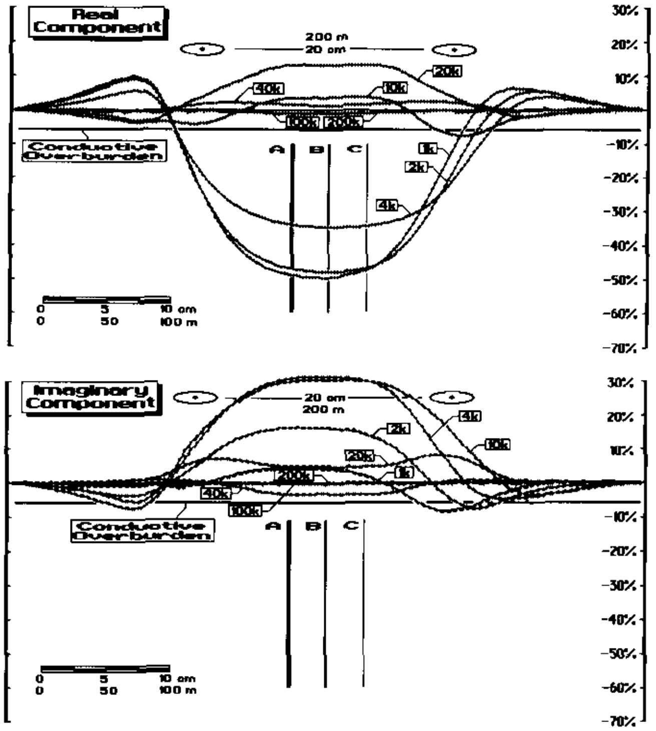

Fig. 5. The overburden caused inversion of the imaginary component of the horizontal coplanar-coil responses to occur even below 1 kHz for all three conductors. A second inversion of the imaginary occurred at 40 kHz. The anomaly was effectively undetectable at 100 and 200 kHz. Baseline displacements have been removed.

conductor B it occurred at slightly higher frequency; for conductor C the phase inversion occurred between 10 and 20 kHz.

The horizontal coplanar separated-coil profiles over the same three conductors with the overburden in place are presented in Figure 5. In this case, marked attenuation of the real component was seen to start at 4 kHz (Figure 5a) as compared to 20 kHz for the coincident-coil responses (Figure 4a). However, the imaginary component responses of Figure 5b show that phase inversion had already occurred for all three conductors at 1 kHz, while by comparison it occurred at 4 kHz for conductor A and above 10 kHz for conductor C in the coincident-coil responses of Figure 4b. As the phase of the field detected by the separated coplanar coils was already inverted at 1 kHz, part of the apparent attenuation of the real component response was due to the rotation of the response vector away from the real component axis. However, the actual attenuation was in fact very strong because at 100 and 200 kHz the real component response of the targets was almost undetectable in Figure 5a while by comparison it was still quite easily seen in the coincident-coil responses of Figure 4 at 200 kHz. The imaginary component responses of Figure 5b show that a second inversion occurred between 20 and 40 kHz and that for the higher frequencies the response was again undetectable as it was in the real component responses of Figure 5a.

The effect of the overburden on the response of the target conductors presented in Figures 4 and 5 is unusually strong and the full display of these effects will not commonly be met in actual field surveys. Only a few cases of inversion of the imaginary component in horizontal coplanar-coil surveys have been published (e.g., Betz, 1976; Lajoie and West, 1977), while inversion of the real component does not appear to have been reported in case histories of any field surveys. As the scaling discussion presented earlier indicates that the free-space responses in Figure 2 can be viewed as representing what will in fact be seen for a full-scale survey (for the same frequencies in the model and the field and a scale factor of 1000:1), then the effects seen in Figures 4 and 5 will also be seen in the field for the same frequencies.

In order to permit a direct comparison of the amount of attenuation and phase rotation detected by the two coil configurations, Figure 6 presents an Argand space display of peak anomaly magnitudes with and without overburden for the vertical coincident coils located over a single vertically dipping thin tabular target of infinite depth and strike extent, while Figure 7 presents the peak responses for the same coils in a separated horizontal coplanar configuration located over the same target at the same depth. In both cases the target and the overburden had identical 480 S conductance. The anomaly magnitudes are quoted with respect to the coupling measured with the coils coplanar at 20 cm separation in free space and it should be noted that the plotting scale in Figure 7 is magnified by a factor of 2 with respect to the plotting scale used in Figure 6. The baseline shifts due to the overburden

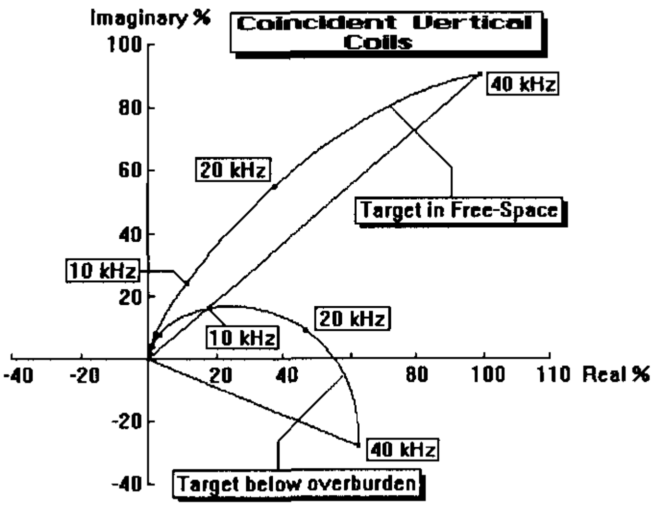

Fig. 6. Argand plots of the coincident vertical-coil response of a vertical tabular conductor of 480 S conductance located below an overburden of equal conductance indicate that phase rotation and attenuation due to the overburden were moderate up to 10 kHz.

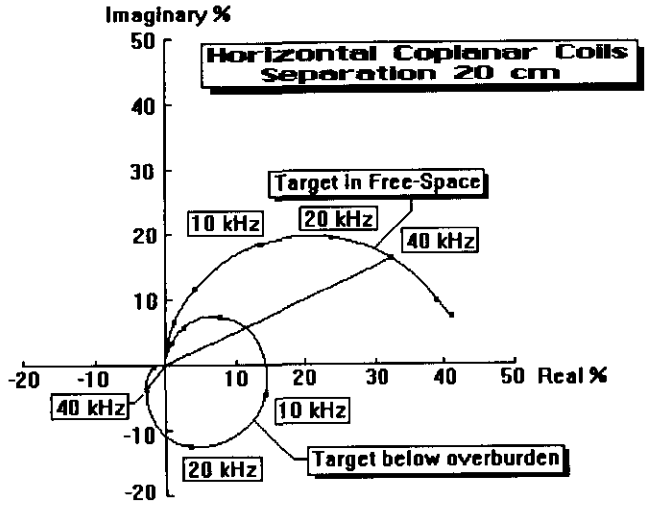

Fig. 7. The separated horizontal coplanar-coil response over the same model used to provide the responses shown in Figure 6. The field vectors for 40 kHz have been emphasized to demonstrate the very strong phase rotation and attenuation detected at that frequency. The corresponding vectors for the coincident-coil response display much less rotation and attenuation.

were subtracted to permit the anomaly magnitudes due to the target alone to be appreciated. The field vectors recorded at 40 kHz have been emphasized in both Figure 6 and Figure 7 to permit the relative phase rotation and attenuation to be appreciated.

Figure 7 demonstrates that use of higher frequencies in separated-coil systems cause a greater range of the effects of an overburden to be observed but to what purpose? When inversion of the real component of the target anomaly is observed then severe attenuation of the detected secondary field from the target will be operating as shown in Figure 7. There appears to be little merit in operating such a system under conditions which diminish the anomalous fields that it is intended to detect. In fact when the conductance of the target and the overburden are comparable as they are in Figure 7, severe attenuation of the target field occurs even when only the imaginary component is inverted so that in terms of the logical objective of maximizing the response of the target there appears to be little need to operate such a system at frequencies (or separations) which cause imaginary component inversion, let alone real component inversion. Thus, it appears that the merit of using higher frequencies in separated-coil systems lies in the determination of the characteristics of the overburden rather than in defining the character of the target.

Table 1 shows the relative attenuation and phase rotation measured at 10, 20 and 40 kHz model frequencies as derived from Figures 6 and 7. It is notable that at all three frequencies the attenuation and phase rotation was significantly less for the coincident-coil system than for the horizontal coplanar-coil system. The 6.67% attenuation at 10 kHz for the coincident-coil system indicates that for all lower frequencies the anomalies due to the target would be very little different in magnitude than if the target was not overlain by an overburden. In addition, the coincident-coil responses for all frequencies below 10 kHz would only be phase inverted for targets of very high conductance. By comparison, the horizontal coplanar-coil responses for the frequencies below 10 kHz would be strongly attenuated and phase rotated to the extent of being phase inverted even for targets with low conductance. This can be appreciated because the imaginary component response of all three targets in Figure 5b were inverted even at 1 kHz, while in Figure 4b the coincident-coil imaginary component responses did not invert until 4 kHz even for the strongest conductor.

Thus, it appears that a coincident-coil system will be able to detect the secondary fields of target conductors through an overburden with less interference from that overburden than a separated-coil system will experience.

It must be stressed again that this ability to see the secondary field due to the target relatively free of the effect of the overburden originates in the minimal path within the overburden that the field propagating to and from the target experiences when a coincident-coil configuration is used and that the vertical-coil configuration will provide a slightly greater advantage in this context than will the horizontal configuration.

In separated coil systems (of any configuration) where the response is presented in a form normalized with respect to the primary coupling, the use of larger coil separation is the normal method for increasing the depth of exploration, but this inevitably causes a conductive overburden to respond as a better conductor so that when such an overburden is present increasing the coil separation only increases the possibility that the target will not be detected. This provides a clear incentive to reduce coil separation and the results presented

Table 1.

	Coincident Coils		Horizontal Coplanar Coils	
Frequency	Attenuation	Phase Rotation	Attenuation	Phase Rotation
10 kHz	6.67%	22.0°	31.19%	65.1°
20 kHz	22.96%	42.2°	61.20%	100.4°
40 kHz	46.76%	59.8°	87.90%	153.8°

here indicate that this can be profitably carried to the point of the coincidence of the two coils.

A further notable comparison of the two configurations is that in the coincident-coil responses (Figures 2 and 4) the relative conductance of the three conductors was clear over the whole frequency range even when the overburden was present. By comparison, the separated-coil responses of Figures 3 and 5 provided little opportunity to identify even the number of conductors, let alone their relative conductance, even if the overburden was not present.

In order to provide a view of the relationship of these results to what can be expected in actual field surveys it may be noted that the horizontal coplanar-coil model results presented in Figure 5a and b display a phase inversion at 2 kHz which is comparable to the phase inversion observed by Lajoie and West (1977) for a frequency of 1777 Hz using a horizontal coplanar-coil (Max-Min) system with a coil separation of 150 m (their figure 1) over a target located in the Abitibi Clay Belt of northeastern Ontario. The target studied by Lajoie and West (1977) was interpreted to be a steeply dipping tabular structure at a depth of 35 m with a 30 S conductance. Hanneson and West (1984) reevaluated this data and found the target depth to be 30 m with target conductance of 31 S overlain by an overburden with a conductivity of 0.068 S/m (i.e., a resistivity of 15 Ω-m) and a thickness of 7.5 m (a conductance of 0.5 S). For a scale factor of 750:1 (i.e., 150 m to 20 cm) and a frequency ratio of 2000:1777 the 480 S overburden used in the model represents a full-scale overburden conductance of 0.72 S. Thus, the model overburden was almost 50% stronger than the overburden that lies over the conductor studied by Lajoie and West. The full-scale conductances represented by conductors B and C in Figures 2 and 4 will be 48 S and 7.2 S, respectively, so that the actual 30 S full-scale conductor can be expected to respond to a vertical coincident-coil system in a manner intermediate to the responses of conductors B and C as shown in Figure 4. However, the phase inversions will be seen at higher frequencies than in the model data because the model overburden was a more effective conductor than the actual overburden at the full-scale site.

The comparison of the 1 and 2 kHz profiles in Figures 4 and 5 indicate that a vertical coincident-coil system operating at frequencies up to 2 kHz in the model sees no phase inversion and that in this frequency range the responses with and without the overburden are indistinguishable. Thus, over the less effective overburden conductor at the site studied by Lajoie and West it can be expected that a vertical coincident-coil system will respond to that conductor as though it were located in free space for all frequencies up to at least 1777 Hz. Ignoring the overburden and applying free-space phasor diagrams such as presented by Duckworth et al. (1993) to the estimation of target conductance should give very good results for frequencies up to 1777 Hz.

This comparison with the field results of Lajoie and West (1977) did not involve a direct attempt to model their data. Such an attempt would have been conducted with a single target rather than the close group of three targets employed in these tests.

It will be necessary to develop appropriate procedures for dealing with the effects of more conductive or thicker overburdens but the 0.5 S overburden at the site used by Lajoie and West (1977) appears to be particularly severe. If that environment represents one of the stronger overburden effects that can be expected in field surveys then as the coincident-coil system will respond to that conductor as though it were in free space for frequencies up to 1777 Hz the need for methods to deal with stronger overburden effects in the responses of a coincident-coil system may be minimal. Thus, it appears that the vertical coincident-coil configuration (with the horizontal configuration only slightly less effective due to the 0.82 D offset at peak anomaly) will indeed be notably insensitive to the effects of overburden on target anomalies, at least for the type of overburden so far reported in case histories of actual field surveys presented in exploration journals. A test of these predictions for the coincident-coil system operated over the conductor used by Lajoie and West (1977) is a clear priority for further work if support for the further development of this device is obtained.

BASELINE DISPLACEMENT

The results presented above indicate that for the lower frequencies commonly employed in mineral exploration the anomaly detected by the coincident-coil system due to a target located below an overburden will be very little different from the anomaly that would be detected if the target was not located below an overburden. However, this response due to the target will be superimposed upon a baseline shift due to the overburden. The profiles presented in Figure 8 illustrate these baseline shifts. The target conductor in this case was a graphite sphere of 9 cm radius (90 m in the full-scale system discussed earlier) located at a depth of 4 cm (40 m). The overburden was a sheet of aluminum foil with a conductance of 480 S (0.48 S) as used in the results presented in Figures 3 and 5. The depth of the overburden below the coils was 2 cm (20 m). In Figure 9 the same data is presented with the baseline displacements removed to permit the target anomaly magnitudes to be compared. Figure 8 demonstrates that while these baseline shifts are strong, the anomalies due to targets located below the overburden can still be readily detected. It is notable in Figure 9 that for frequencies up to 2 kHz the anomalies due to the target were not appreciably altered. The slight enhancement of the real component responses when the overburden was in place can be ascribed to the rotation of the field vector towards the real component axis as in Figure 6.

It is certain that if the overburden varies in thickness or conductivity or depth this will create variations in the baseline shifts which may make it difficult to identify the anomaly due to an underlying target. If the target is located just below the overburden then its response should be readily identified, but if the overburden lies at surface and the target at significantly greater depth then the noise due to the overburden may be

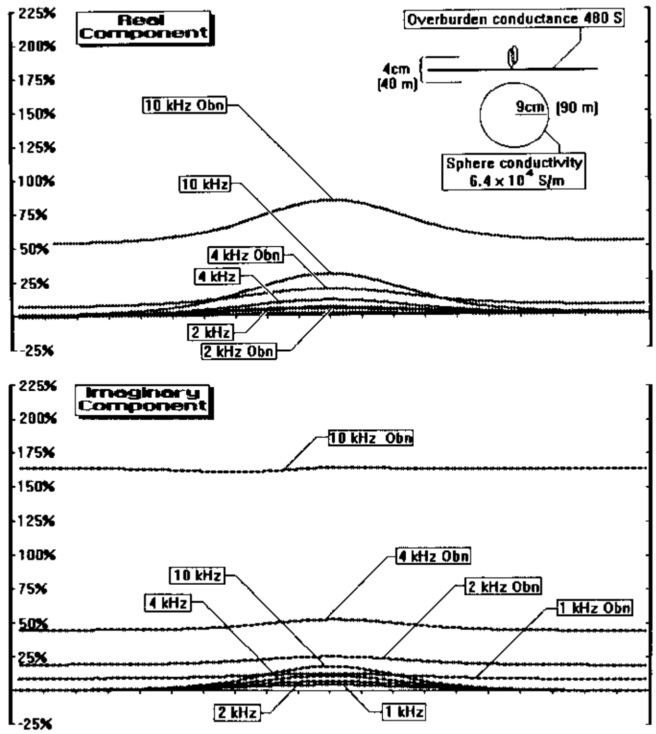

Fig. 8. The coincident vertical-coil responses over a sphere target for 1 to 10 kHz. The baseline displacements are as recorded.

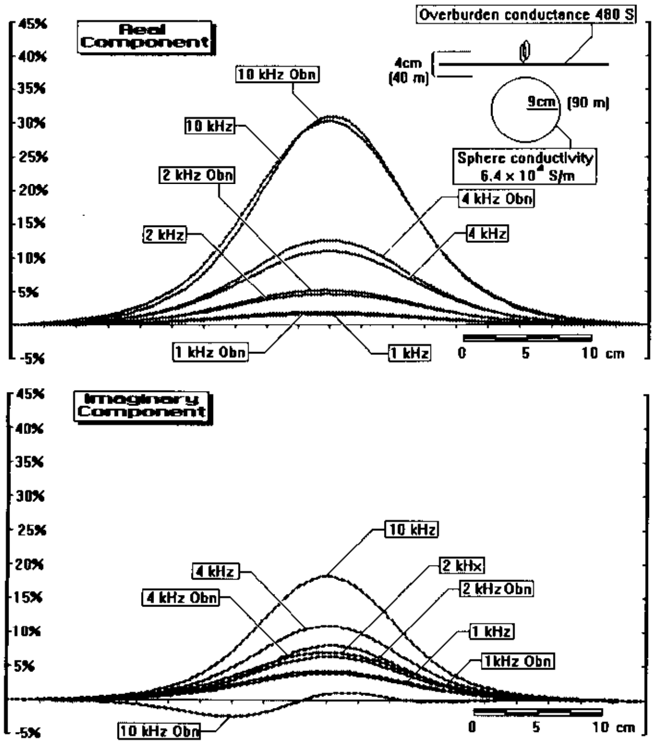

Fig. 9. Removal of the baseline displacements from the data presented in Figure 8 indicates that the overburden had little effect on the anomaly due to the target for frequencies up to 4 kHz.

overwhelming. However, in such circumstances a separated-coil system may fare no better, particularly as increasing coil separation causes the separated-coil systems to respond more strongly to near-surface flat-lying conductors. It seems probable that the different spatial wavelength of the anomalies from the shallower overburden and the deeper targets will allow the coincident-coil responses of the targets to be separated from the near-surface noise but this is an area of development of the coincident-coil device which remains to be pursued. It may be noted in this context that the separated-coil systems provide an automatic rejection of surface noise by virtue of the separation of the coils so that in this area of operation the separated-coil systems enjoy an advantage over the coincident-coil system.

DEPTH DETERMINATIONS

When using a conventional horizontal coplanar-coil exploration system in the presence of an overburden, the determination of the depth of a target requires that the characteristics of the overburden be determined in order that the correct anomaly index diagram for depth and conductance estimation may be selected in the manner described by Hanneson and West (1984). This method of depth determination is based upon the magnitude of the anomaly. By comparison, the coincident-coil responses provide depth estimates based upon the geometry of the profiles rather than on the magnitude of the responses. The particular geometry that is employed is the separation of peaks on profiles obtained over the target with the coincident coils operated in the horizontal attitude as described by Duckworth et al. (1993). Horizontal coincident-coil profiles obtained with the modelling system at frequencies up to 10 kHz with and without an overburden displayed no measurable difference in the peak separations when the overburden was in place even if the imaginary component was inverted by the presence of the overburden. Thus, it appears that within the range of conditions likely to be met in the field, the method of depth determination described by Duckworth et al. (1993) can be applied using the same gradient factors that were determined for a target in free space regardless of the presence of an overburden. This lack of sensitivity of profile geometry to an overburden was demonstrated by Duckworth et al. (1991) using field data acquired by Betz (1976) which was phase inverted by an overburden but which gave geometrically derived depth values which were in good agreement with drilling information.

DISCUSSION

There can be no doubt that the coincident-coil system will respond to an overburden alone much more strongly than will a separated-coil system and that variations of the conductivity of that overburden will produce unwanted noise in the data. At this time no field tests have been conducted which allow the level of this problem to be evaluated. However, the user of the coincident-coil device will have the option of using low frequencies to minimize the response of conductive overburden while being confident that the response from targets below that overburden will still be strong. This can be appreciated by the fact that at the lowest frequency available in the tests presented here the response from the good conductors was still approximately 4 times stronger than the separated-coil response and in field tests of prototypes the system has responded well to conductors when operated at 300 Hz (Duckworth et al., 1993).

The potential user of this system may also have legitimate concern for the practical implementation of the coincident-coil device. Thermal and mechanical stability of the system is vital. An early prototype changed its reading every time the sun came out. However, successful field tests of prototypes of the coincident-coil system have been conducted as described by Duckworth et al. (1993) but these did not include tests over any target located below a conductive overburden. The further development of this device will be technically very demanding as there is no doubt that maintaining the coils in a zero-coupled condition in a device which must withstand extremes of temperature and possible rough handling will be difficult.

CONCLUSIONS

The results presented here indicate that the list of operational advantages of the coincident-coil system can be expanded to include the following:

1. Low sensitivity to the effect of a conductive overburden (of the type so far reported in field surveys) on the response of a target located below that overburden for the lower frequencies commonly employed in mineral exploration surveys.
2. The ability to provide clear indications of the relative conductance of closely spaced target conductors even in the presence of a very severe overburden effect.
3. The notable spatial resolving power of the coincident-coil system appears to be unimpaired by the presence of a conductive overburden. This can be seen in the detection of three separate anomalies over the three test conductors at all frequencies with or without the overburden while the separated-coil system responses would not even have permitted an interpretation in terms of the number of conductors with or without the overburden.
4. Over the range of frequencies commonly employed in metallic mineral exploration the methods of depth estimation developed for targets in a free-space environment will give good results.

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