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THE RESPONSE OF STEEPLY DIPPING TABULAR CONDUCTORS LOCATED IN CONDUCTIVE HOST ROCKS WHEN DETECTED BY HORIZONTAL COPLANAR COIL AND VERTICAL COINCIDENT COIL ELECTROMAGNETIC EXPLORATION SYSTEMS

K. DUCKWORTH* AND E.S. KREBES **

ABSTRACT

A physical scale model study of the comparative performance of the horizontal coplanar and vertical coincident coil systems has been conducted over a steeply dipping tabular conductor. The conductor was located first in free-space and then in a conductive host with a view to permitting an investigation of the influence of current gathering on the response of the conductor. In the presence of the conductive host the response of the conductor displayed two dispersions. The first was due to the conductor itself and was present throughout the frequency range, the second occurred at high frequency. This high frequency dispersion can be ascribed to the development of the gathering of current from the host into the target conductor. Low frequency responses for both coil systems displayed phase behaviour that is characteristic of current gathering. However, the amplitude behaviour at low frequencies did not appear to be capable of explanation by means of the current gathering concept. The results confirm earlier studies that showed that the strength of response provided by the coincident coils is greater than the response provided by the separated horizontal coplanar coils. The results also confirm earlier studies that have shown notably superior spatial resolution of anomalies provided by the coincident coil system. This high level of spatial resolution is retained by the coincident coil responses when the conductive host and consequent current gathering are present.

INTRODUCTION

The frequency-domain electromagnetic response of mineral targets located in conductive host rocks has been discussed in a number of earlier studies (e.g., Guptasarma and Maru 1971, Gaur et al. 1972, Lajoie and West 1976, Hanneson and West 1984, Duckworth and O'Neill 1989). In all of these earlier studies the most notable feature was the strong enhancement of the response when the target conductor was placed in a conductive host environment. This phenomenon is caused by the gathering of induced current from the host rock into the more conductive target. The result of this is that the total current induced and gathered into the target conductor, can be considerably stronger than the current that would be induced into the conductor if it were located in a resistive host. This enhanced current causes a corresponding enhancement of the secondary field radiated by the target and a desirable enhancement in the detectability of the target. However, the enhancement that the current gathering effect produces, tends to be dominant in the quadrature component so that the responses display in-phase to quadrature ratios that are poorly representative of the quality of the target conductor. Also notable in the earlier studies was the markedly greater strength of the current gathering effect when observed with fixed loop systems [Lajoie and West (1976), Duckworth and O'Neill (1989)] than when observed with moving source devices [Guptasarma and Maru (1971), Hanneson and West (1984)]. This difference indicates that the current gathering effect is heavily dependent on the configuration of the exploration device. Therefore it is to be expected that even within the moving source class of devices, the observed current gathering effect will show a strong dependence on the particular coil configuration of each device.

The study reported in this paper is intended as an extension of a series of studies that have investigated the exploration merits of an electromagnetic device which employs a frequency-domain coincident coil concept. [Duckworth et al. (1991), Duckworth et al. (1993), Duckworth (1994), Duckworth and Krebes (1997) and Duckworth and Krebes (1998)]. The approach adopted in these studies has been to compare the coincident coil device with the standard horizontal coplanar coil device. As the present study proceeded, it became clear that the results showed previously unreported behaviour even for the well established standard exploration device, so that the results will be of interest in a wider context. The earlier studies employed theory and physical scale modeling to investigate the response of the two coil configurations when operated in conditions where the current gathering effect was not present. Those studies involved steeply dipping tabular targets located in free-space and located in free-space below a conductive overburden but not in contact with that overburden. The present study is based upon physical scale modeling and treats targets located in conductive host rocks where current gathering can operate.

*Department of Geology and Geophysics, University of Calgary, 2500 University Drive N.W., Calgary, Alberta, Canada T2N 1N4, (403) 220 7375, Fax (403) 284 0074, E-mail duckwrth@geo.ucalgary.ca, World Wide Web http://www.geo.ucalgary.ca/~duckwrth/kd.html.

**Department of Geology and Geophysics, University of Calgary, 2500 University Drive N.W., Calgary, Alberta, Canada T2N 1N4, (403) 220 5028, Fax (403) 284 0074

A coincident coil frequency-domain device might appear to be a difficult concept to implement but it becomes practical if separate receiver and transmitter coils are employed in a zero coupled configuration. This zero coupled configuration has been described in detail by Duckworth et al. (1993), Duckworth (1994), and Duckworth and Krebes (1997).

A comparison between the vertically oriented coincident coil device and the conventional horizontal coplanar coil configuration was adopted for this series of studies because the primary application of the coincident coil device will be as a ground borne system. Among the ground borne systems, the horizontal coplanar coil configuration is the one that has been most extensively studied [e.g., Hedstrom and Parasnis (1958), Lowrie and West (1965), Guptasarma and Maru (1971), Gaur et al. (1972) and Hanneson and West (1984)] and therefore provides a standard against which any new system must be evaluated. As detailed in the earlier papers concerning the coincident coil device, the use of the vertical orientation of the coincident coils is the logical orientation of this device when exploring for steeply dipping structures because it provides the maximum possible coupling to that type of structure. In this regard, the concept can be compared to the wing tip airborne configuration which also employed vertical coil orientation to achieve maximum coupling to steeply dipping structures.

The coincident coil configuration is equally able to function with the coils in the horizontal or vertical attitude, however, while the horizontal attitude has particular application in the determination of target depth and dip as described by Duckworth et al. (1993), it will not be employed in the primary search for steeply dipping targets. The reasons for this are the markedly better spatial resolution and stronger response provided by the vertical coil orientation [Duckworth and Krebes (1998)]. Therefore the vertical coincident coil orientation will be the one that is used in reconnaissance exploration and it is the configuration that must be compared with the conventional reconnaissance configuration that being the horizontal coplanar coil configuration.

As the implications of the unusual results obtained in this study are potentially relevant to all electromagnetic exploration systems, we felt it necessary to conduct the whole study several times in order to establish that the observed effects were quantitatively repeatable. Repeating the tests required that several hundred litres of brine that simulated the conductive host remained unchanged. Consequently changes of host conductivity were not attempted in this study.

The present study employed a modeling system which has provided results in earlier studies that are in close agreement with theoretical model results for high conductance targets located in free-space environments [Duckworth et al. (1993); Duckworth and Krebes (1995), Duckworth and Krebes (1997)] and with field results [Duckworth and O'Neill (1992)]. It was hoped that the present study of targets located in a conductive host, would be able to replicate the results of earlier work by other authors on the horizontal coplanar coil configuration; particularly the work of Hanneson and West (1984). Regrettably the choice of materials necessary in physical modeling, prevented a direct comparison with the earlier theoretical study.

Attempts to conduct scale model studies of conductive environments pose special problems in the materials that can be used. In this context, we found that metal models were unsuitable because of corrosion of the metals by the brine solution used to simulate the conductive environment. Stainless steel models were tested and results for one such model are provided in this discussion but shown to be unsuitable for quantitative evaluation of the performance of electromagnetic systems. Graphite was found to be the best model material as it is well suited to the requirement that the model remain immersed in the highly corrosive concentrated brine for several weeks without being affected by the brine. However, the simulation of truly thin tabular conductors is impractical with graphite conductors because thin sheets of solid graphite are difficult to produce and would be very fragile.

While the series of papers Duckworth et al. (1991), Duckworth et al. (1993), Duckworth (1994), Duckworth and Krebes (1997) and Duckworth and Krebes (1998), have detailed the performance of the coincident coil device, no commercial version of the coincident coil frequency-domain device is currently available. This evaluation of the performance of the device before it is widely available, has been provided in order to demonstrate that the coincident coil concept will offer significant exploration advantages when the device becomes available to the exploration industry.

Results

Horizontal Coplanar Coil responses

Profiles of the response of a graphite plate as detected by a horizontal coplanar coil configuration are shown in Figure 1. The plate was located first in free-space and then in a conductive host environment with a conductivity of 14.5 S/m (0.069 Ω-m). Figure 1 displays results for only a single target depth of 2 cm but for a range of frequencies. A complex space plot of peak anomalies is shown in Figure 2 for a range of both depths and frequencies. The peak anomaly plots for the free-space and conductive host cases are superimposed on each other in Figure 2 rather than being shown separately. The graphite plate was sufficiently extensive (1 m x 0.3 m x 0.013 m) that its behaviour was identical to that of a plate of infinite strike and depth extent. The plate thickness of 13 mm allowed it to behave approximately as a thin conductor at lower frequencies. However, at 400 kHz the 6.3 x 10^4 S/m conductivity of the graphite model gave a skin depth of 3.2 mm so that the thickness of the plate was more than 4 times greater than the skin depth at that frequency. As thin conductor behaviour requires that the ratio of plate thickness to skin depth be less than 0.1 it was inevitable that the conductor was behaving as a thick conductor at 400 kHz.

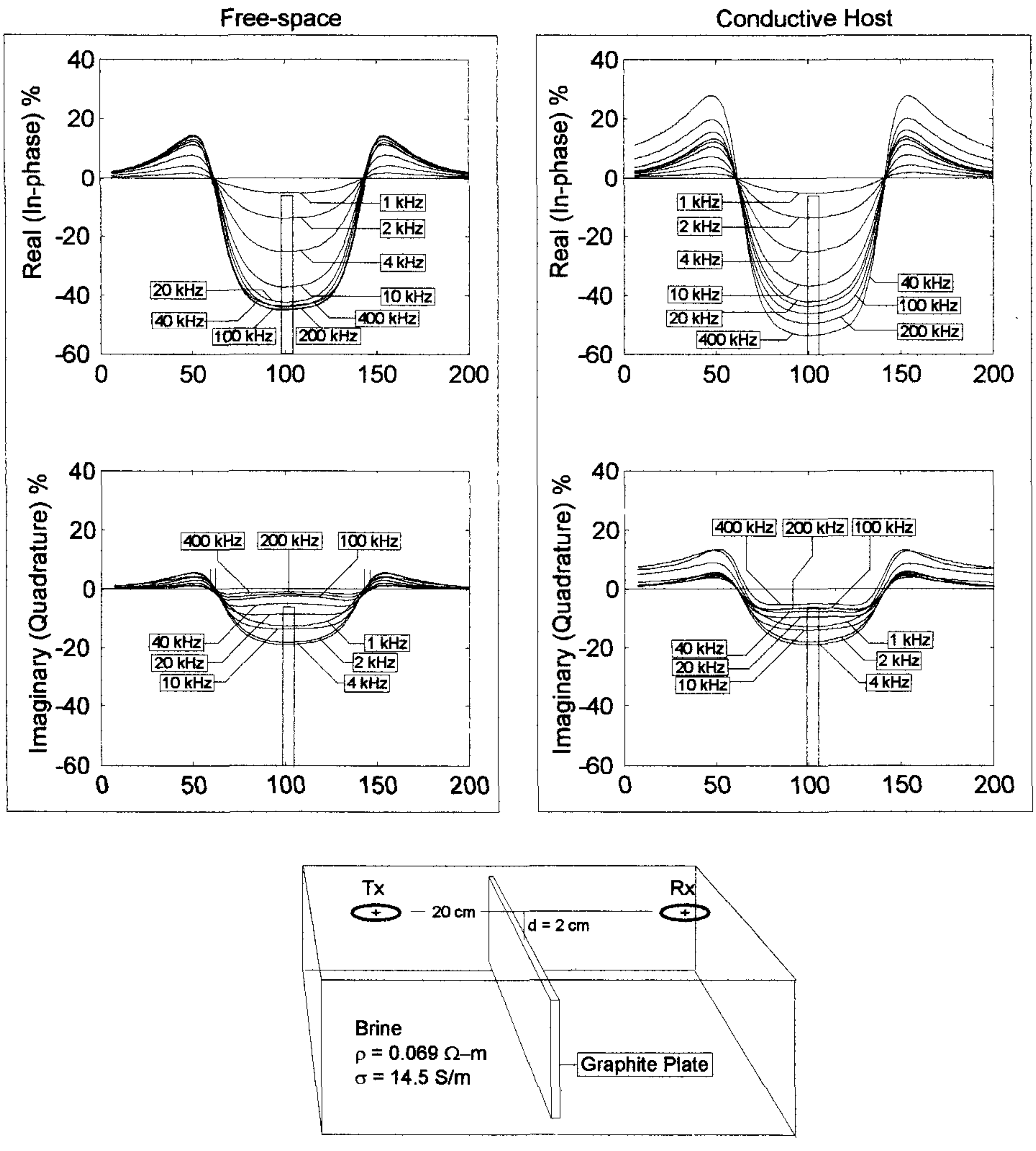

Fig. 1. Responses obtained with separated horizontal coplanar coils at a separation of 20 cm over a graphite slab target (dimensions 1 m x 0.3 m x 0.013 m) located at a depth of 2 cm first in a free-space host and then in a host of 14.5 S/m conductivity for a range of frequencies from 1 kHz to 400 kHz.

The anomaly magnitudes plotted in the complex plane of Figure 2 were measured at the centre of the negative response on each profile. For the responses where the conductive host was present, the anomaly magnitudes were measured with respect to the response at locations remote from the target, i.e., they were measured with respect to the elevated baseline response caused by the conductive host alone. However it must be stressed that the magnitudes of these anomalies were normalized with respect to the free-space field at the receiver coil.

The profiles of Figure 1, show that at locations outside the

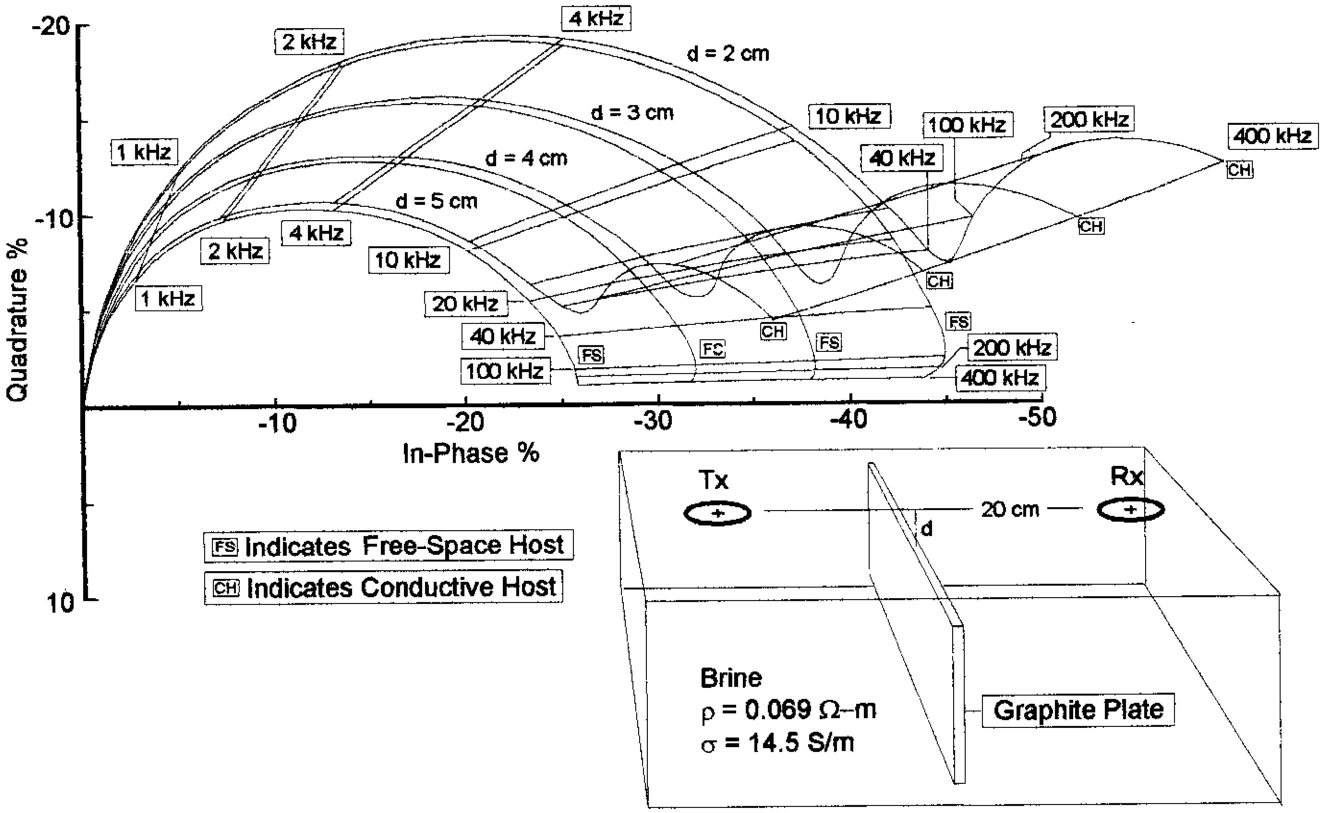

Fig. 2. Complex space plots of peak response obtained over a graphite slab target located at depths ranging from 2 to 5 cm and a frequency range from 1 kHz to 400 kHz using separated horizontal coplanar coils at a separation of 20 cm. The free-space host case and the conductive host case are superimposed for ease of comparison.

main anomaly, the presence of the conductive host displaced the whole response in the positive direction for all frequencies. Thus the anomalies due to the target were superimposed on this general positive baseline shift due to the host. It is also evident in Figure 1, that when the conductive host was present, the higher frequency responses of the target were strongly enhanced.

Enhancement of the response by the presence of the conductive host was expected but the non-uniform character of this enhancement revealed by plotting peak anomalies in complex space as shown in Figure 2, was not expected. This lack of uniformity is shown in Figure 2 by the sudden onset of very strong enhancement for frequencies above 40 kHz. This kind of response does not appear to have been reported in any previously published studies.

For the frequency range from 1 to 40 kHz, Figure 2 shows only a mild magnitude enhancement and a slight anti-clockwise phase rotation (phase lead) for all the response vectors when the conductive host is present. This behaviour appears to be in agreement with responses reported by Hanneson and West (1984) for low host conductivities.

For the model frequencies above 40 kHz, the responses show not only a much stronger enhancement but also a marked increase in the anti-clockwise phase rotation up to 200 kHz followed by a trend to clockwise phase rotation at the highest frequency. It is also notable that the baseline shifts seen in Figure 1 show a similarly pronounced enhancement and distinct onset which begins at 40 kHz. The fact that the baseline displacements show this strong onset at 40 kHz indicates that below this frequency, current induced into the host alone was so weak as to contribute very little to the total current flowing in the target. However the phase behaviour of the responses below 40 kHz is characteristic of a current gathering effect rather than of the effects due to propagating the field through a conductive screen around the target. This can be seen because the phase displacements are all anticlockwise (i.e., phase lead) in Figure 2, whereas a conductive screen without current gathering, produces uniform clockwise phase rotation (phase delay) as described by Lowrie and West (1965) and by Hanneson and West (1984). This suggests that current gathering was in fact operating at the frequencies below 40 kHz but that it became significantly stronger above that threshold frequency due to a corresponding onset of strong induction of current into the host medium. This onset of strong response at 40 kHz was seen in the response of the host without the target being present [Figure 6(a)] so that the target was not responsible for this effect.

The sudden onset of strong enhancement of the anomaly magnitude at 40 kHz results in the development of a second

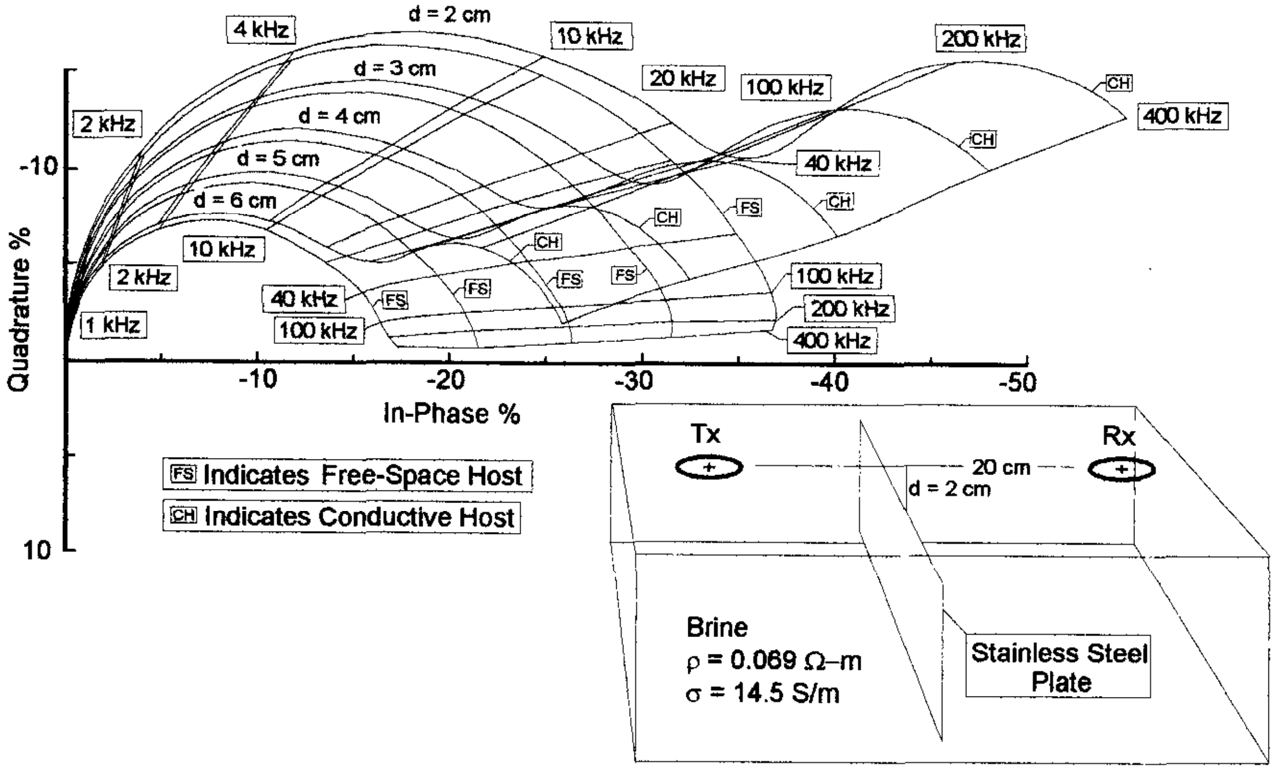

Fig. 3. Complex space plots of peak response obtained over a stainless steel target located at depths ranging from 2 to 5 cm and a frequency range from 1 kHz to 400 kHz using separated horizontal coplanar coils at a separation of 20 cm. The magnitudes in the main dispersion are too small indicating that possibly the magnetic permeability of the steel was affecting the response. These responses can not be used in quantitative interpretation of full scale field data.

dispersion. This second dispersion would be understandable as being the dispersion due to the host medium alone, except that if that is the case, then the effects below 40 kHz should be negligible and should not show the characteristic phase lead of a current gathering effect. The phase lead seen below 40 kHz was verified by repeated tests over the whole frequency and depth range. It proved to be notably consistent.

Following Hanneson and West (1984) the response parameters of the host and target are defined as follows:

$$\alpha_{\text{Host}} = \sigma_{\text{Host}}\mu\omega L^2 \text{ and } \alpha_{\text{Target}} = \sigma_{\text{Target}} t\mu\omega L$$

Where	L	is the coil separation.
	σ	is conductivity.
	μ	is magnetic permeability.
	ω	is angular frequency.
	t	is the thickness of the target.

Using these definitions, the ratio of the response parameters of the target and host used in this study was 286.9:1 so that it is probable that the response of the target was able to approach its inductive limit before the host response was able to move away from its resistive limit. This would explain the development of a double dispersion as seen in Figure 2. In actual field exploration it appears possible that ratios of target to host response parameters may quite commonly be of the order of the ratio used in this study. For example a tabular conductor with a thickness of 5 m and a conductivity of 10 S/m located in a host with a conductivity of 0.002 S/m (500 ohm-m) would give:

$$\frac{\alpha_{\text{Target}}}{\alpha_{\text{Host}}} = \frac{\alpha_{\text{Target}} t\mu\omega L}{\sigma_{\text{Host}}\mu\omega L^2} = \frac{\sigma_{\text{Target}} t}{\sigma_{\text{Host}} L} = \frac{10.5}{0.002.100} = 250$$

Thus it may be expected that effects of the type seen in Figure 2 could be quite commonly encountered. If such a response was encountered it would result in very unusual effects in the interpretation of high frequency data. For instance, a reduction of frequency would cause the response to follow one of the constant depth contours towards the origin so that starting at the highest frequency, the conductor would appear to respond as a slightly poorer conductor (i.e., in the equivalent of the model frequency range from 400 kHz to 200 kHz). This would be expected but then the response would show a sharp trend towards the appearance of that of a better conductor as the frequency was reduced further (i.e., in the equivalent of the model frequency range from 200 kHz to 40 kHz). This would be followed by an almost equally sharp

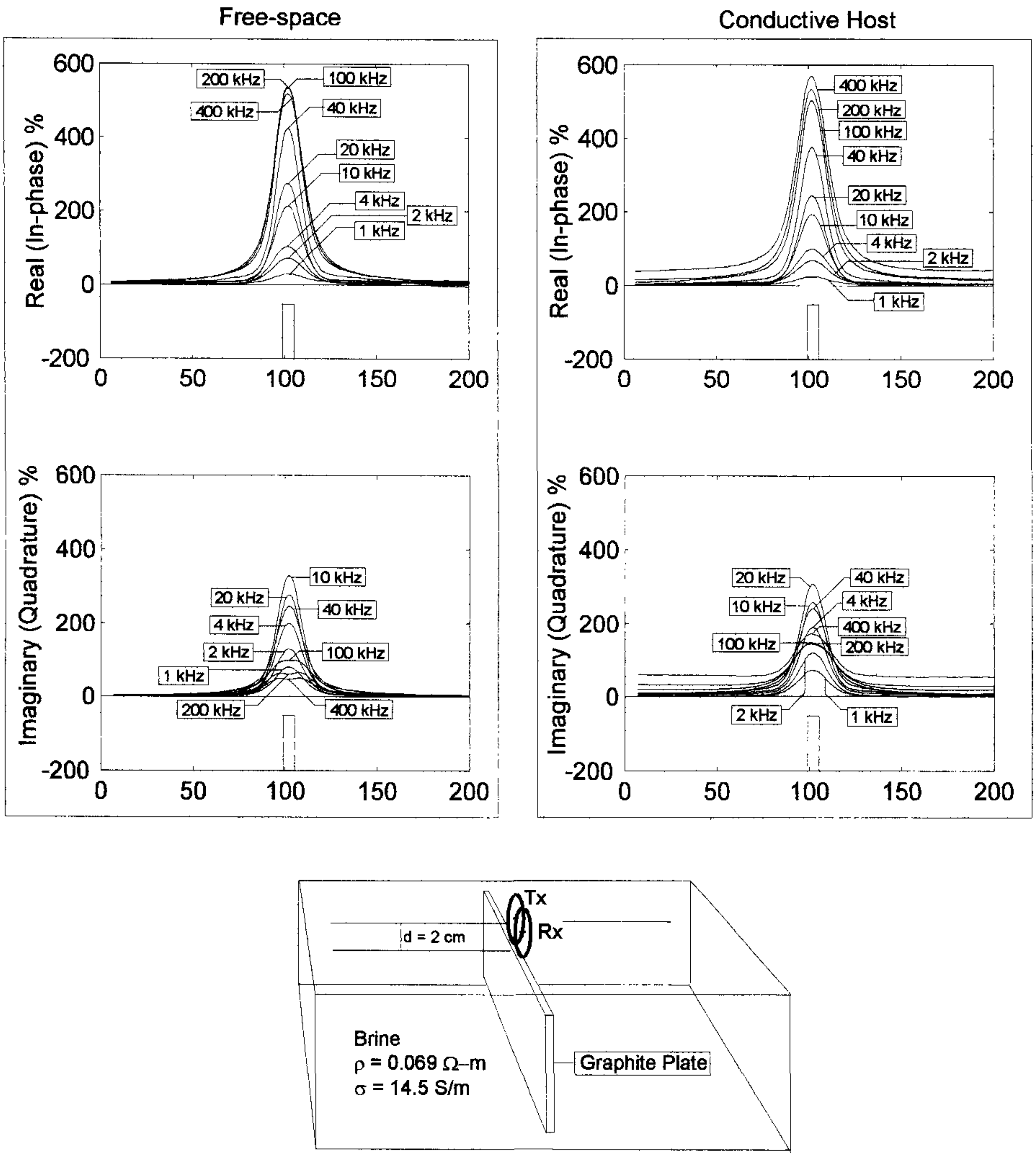

Fig. 4. Responses obtained with the same model coils re-configured to the vertical coincident orientation and operated over a graphite slab target located at a depth of 2 cm first in a free-space host and then in a host of 14.5 S/m conductivity for a range of frequencies from 1 kHz to 400 kHz. The plotting scales of Figures 1 and 4 should be noted. The much greater strength of response for the vertical coincident coils results from their much closer proximity and better coupling to the target at peak anomaly than is achieved by the separated coils.

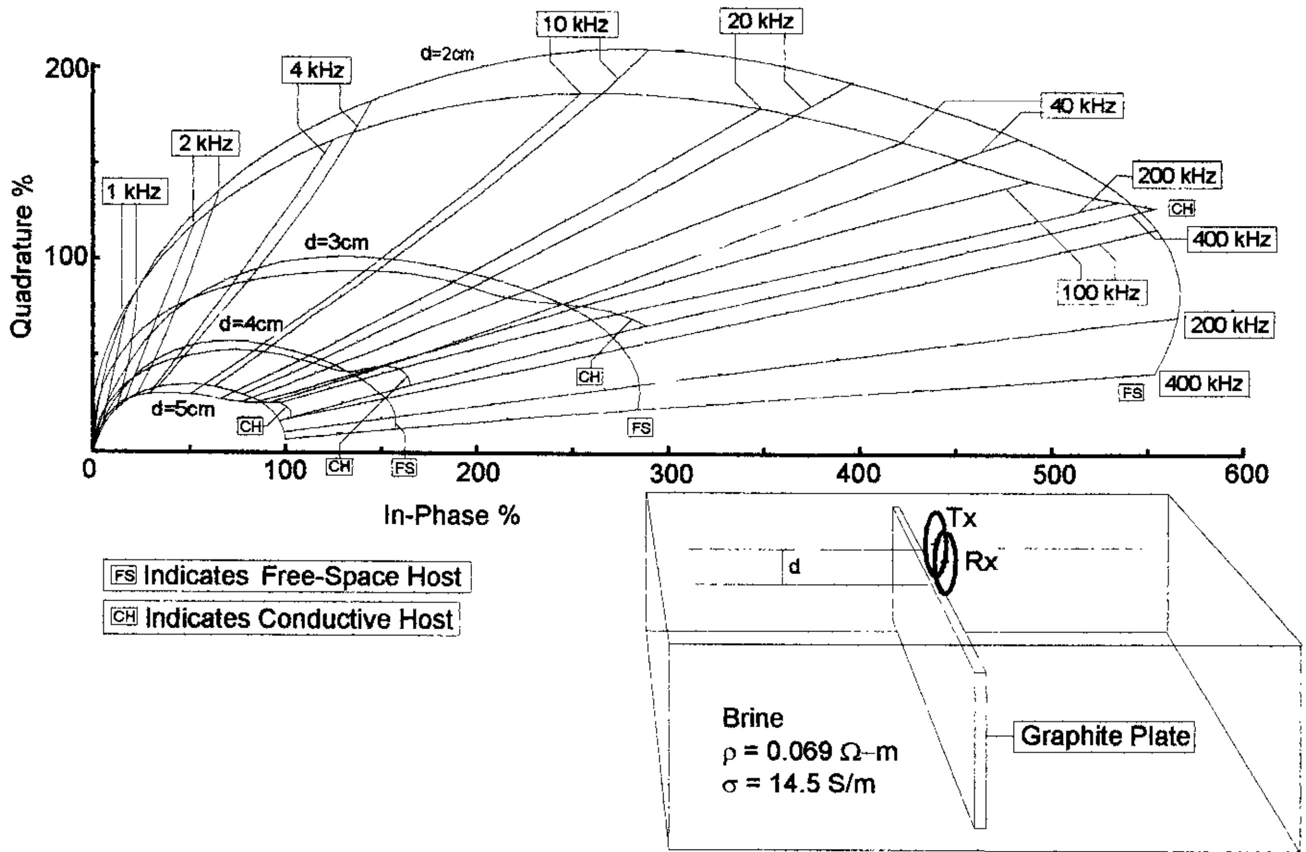

Fig. 5. Complex space plots of peak response obtained over a graphite slab target located at depths ranging from 2 to 5 cm and a frequency range from 1 kHz to 400 kHz using vertical coincident coils. The free-space host case and the conductive host case are superimposed for ease of comparison. The plotting scales of Figures 2 and 5 should be noted.

trend towards the characteristics of a poorer conductor (i.e., in the equivalent of the model frequency range below 40 kHz). It seems very probable that the interpreter would find such conflicting behaviour confusing. Thus it appears that the physical model results presented here will be relevant to conditions that can be found in the field particularly when operating at frequencies up to 50 kHz as in some modern equipment.

The response in Figure 2 of the plate in free-space also displays an unanticipated effect, this being the slight loss of magnitude over the frequency range from 100 kHz to 400 kHz (seen as a curling of each depth contour towards the origin at high frequency). It is probable that this effect is caused in part by a transition in the behaviour of the plate from thin to thick conductor response at higher frequencies. This results in a slight tendency for the centre of the negative part of the anomaly to pull up and thereby diminish the anomaly at its centre, as the system begins to respond to the two edges of the plate separately at the higher frequencies. However, even in the case of a thin conductor, this kind of pull up at the centre of the anomaly is often seen with targets which are located at small depth to coil separation ratios. It is particularly marked for profiles obtained from a theoretical model consisting of a current filament as shown by Duckworth (1988) and by Duckworth and Krebes (1998) and for a theoretical thin plate model as shown by Weidelt (1983). An example of this pull up effect is seen at the centre of the higher frequency imaginary component profiles of Figure 1 for the target in free-space.

An additional indication of the transition to thick conductor behaviour in the free-space case, is the slight widening of the anomalies at higher frequencies as indicated by the increased separation of the crossover points in Figure 1. A thinner graphite plate would have avoided this thick conductor effect but the plate had to be sufficiently thick to be capable of standing free in the brine tank while also not being too fragile to handle.

A stainless steel plate model was tested and the results are presented in Figure 3. The plate was of 0.8 mm thickness and sufficiently extensive both laterally and vertically that no response was detectable from the ends or bottom edge. As can be seen in Figure 3, the response of this plate also showed a similar sudden onset of the enhancement of response at the same threshold frequency of 40 kHz. The feature which makes these responses unrepresentative of pure conductors is the overall attenuation of the response. As the response approached the inductive limit in the free-space case, the responses should have approached the response of a perfectly conductive thin conductor yet they are approximately 20%

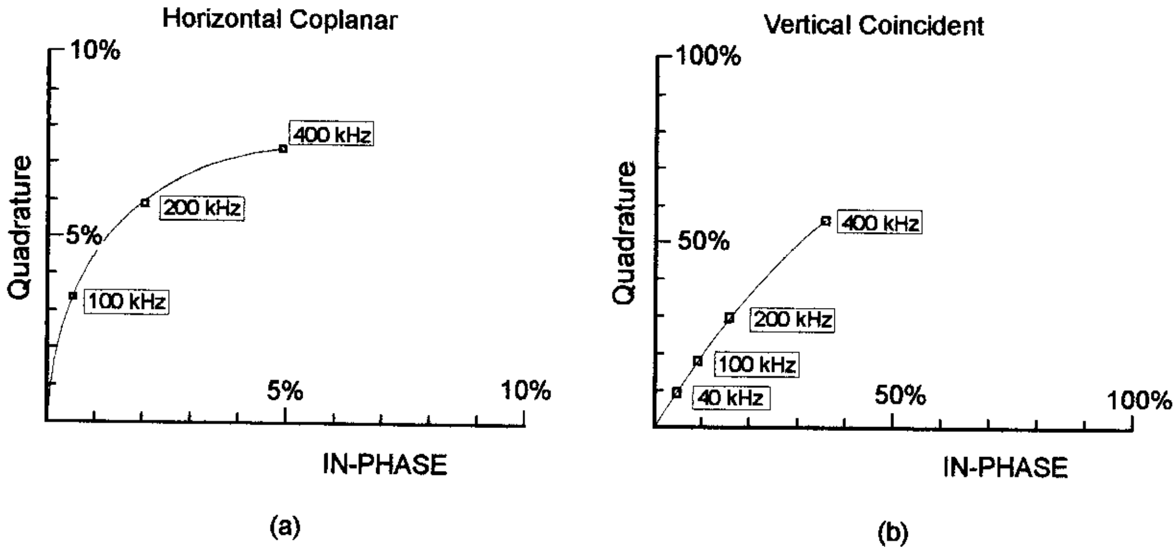

Fig. 6. Complex space plots of the response of the conductive host alone as detected by the coils in the separated horizontal coplanar configuration (a) and then in the vertical coincident configuration (b) for a range of frequencies and a depth of 2 cm.

weaker than the theoretical response for all depth values. In other studies using aluminum conductors Duckworth and Krebes (1995) this physical model system gave very good quantitative matches to perfect conductor theory so that this overall attenuation can be ascribed to the physical properties of the stainless steel. In this context it appears that it is most probable that the magnetic susceptibility of the stainless steel was not equal to that of free-space and that this resulted in the attenuated response. As these responses were recognized as having little quantitative value the cause of this loss of response was not pursued further. However, one quantitative aspect of this response is notable that being that the second dispersion is comparable in magnitude to that observed for the graphite model in Figure 2. This suggests that the amount of current gathered by the stainless steel and graphite conductors was approximately equal despite the fact that the first dispersion had less overall magnitude for the stainless steel.

The fact that the onset of the second dispersion occurred at the same frequency and was approximately equal for both graphite and stainless steel, is an additional indication that this effect was not related to the material used in the target model. Thus the effect appears to be related to the conductivity of the host and it is expected that if that conductivity could be increased, the onset of the second dispersion would occur at lower frequency. The conductivity of the brine used in these model tests was as high as practical with a concentrated brine so that investigations of higher host conductivity were not possible. Reductions in conductivity would have been possible but they were impractical due to the large volume of brine used to simulate the conductive host and the need to maintain the host at a constant conductivity in order that the whole experiment could be repeated several times to establish repeatability.

In the theoretical model responses published by Hanneson and West (1984), the response of a vertical sheet for a fixed ratio of the target to host response parameters, showed uniform progressive enhancement of response as the frequency was increased as opposed to the sudden onset of particularly strong enhancement seen here. However in the study provided by Hanneson and West, the ratio $\alpha_{\mathrm{Target}} / \alpha_{\mathrm{Host}}$ did not exceed 64 and the authors indicated that the theoretical model could not be used at higher values of this ratio so that their study did not treat the $\alpha_{\mathrm{Target}} / \alpha_{\mathrm{Host}}$ ratio of 289.6 used in the present study. In addition, the theoretical model study provided by Hanneson and West, used α_{Host} values as high as 16. In contrast, the brine used to provide a conductive host for the model conductors in the present study gave a maximum value of α_{Host} of 1.83 at 400 kHz with the 20 cm separation used with the horizontal coplanar coils. Consequently the physical model responses presented here do not show the phase inversion which was shown by Hanneson and West's theoretical results for α_{Host} values greater than 4. The trends shown at the higher frequencies in Figures 2 and 3 suggest that phase inversion would be reached if the model frequency was increased by an order of magnitude.

In the physical scale model study provided by Guptasarma and Maru (1971) the $\alpha_{\mathrm{Target}} / \alpha_{\mathrm{Host}}$ ratio used in their figure 8 was as high as 53,352:1 which suggests that their target was almost certainly responding at its inductive limit before the response of the conductive host that they used had even begun to respond. This is confirmed by their curve A for the target in free-space.

Vertical Coincident Coil responses

Response profiles obtained over the same graphite target with the same model coils re-configured to the vertical coincident configuration are shown in Figure 4 for a target depth of 2 cm and a range of frequencies. The anomaly magnitudes are presented as percentages of the primary coupling of the same coils when used in the horizontal coplanar configuration at the separation of 20 cm that was used in the modeling with the separated coils. This form of data presentation provides a direct quantitative comparison between the secondary fields detected by the two configurations of the coils as described in detail by means of a theoretical model by Duckworth and Krebes (1998).

Comparison of Figures 1 and 4 demonstrates that the vertical coincident coils provide considerably better spatial resolution of the response of the target than do the separated horizontal coplanar coils. This confirms earlier results discussed by Duckworth et al. (1993) for targets in free-space and by Duckworth (1994) and Duckworth and Krebes (1998) for targets located below a conductive overburden. This advantage in spatial resolution for the vertical coincident coils is clearly retained even when the target is in contact with a conductive host.

The much stronger responses provided by the vertical coincident coils in Figure 4 than are provided by the horizontal coplanar separated coils in Figure 1 (as can be seen by comparing of the plotting scales) are understandable because of the relative geometry of the two coil configurations with respect to the target. At peak anomaly the vertical coincident coils were located directly over the target so that the distance between the target and the vertical coincident coils was 2 cm which was the depth of the target in both Figure 1 and Figure 4. By comparison, at peak anomaly, the separated horizontal coils with a separation of 20 cm, were each located at a horizontal distance of 10 cm from the target, i.e., at a distance equal to five times the depth of the target as indicated in Figure 1. In addition, at peak anomaly, the vertical coincident coils were coplanar with the target as shown in Figure 4. By comparison the separated horizontal coplanar coils when at their position of peak anomaly, were oriented with the coil planes perpendicular to the plane of the target as shown in Figure 2. This orientation perpendicular to the plane of the target and the 5 times greater distance from the target inevitably resulted in the separated coils being significantly less well coupled to the target than the vertical coincident coils.

Users of the separated horizontal coplanar coil type of device may argue that the response of that type of device to a target at a fixed depth can be increased by increasing the separation of the coils while the coincident coil device would not be able to improve its response in any way. This suggests that the conventional device would be able to surpass the coincident coil device simply by increasing coil separation. That this would not be the case is made clear by considering the absolute strength of the secondary field that each device would detect. Increasing the separation of the horizontal coplanar coils with a target at a fixed depth can only diminish the secondary field detected by that coil system while the secondary field detected by the coincident coils would be constant.

If both sets of responses are rendered dimensionless by dividing by a common normalization factor, and if that factor is constant, then the coincident coil normalized response will remain constant while the separated coil normalized response will decline as the coil separation increases. If however the common normalization factor is based upon the primary coupling between the separated coils, then this factor will decline as coil separation increases. Applying this declining factor to the constant secondary field detected by the coincident coils will cause the normalized output for that coil system to increase. It will also cause the familiar increase in the normalized output of the separated coil system. However, as the secondary field detected by that system must decline as coil separation increases, the increase of the normalized output for the separated coils can only happen if the rate of decline of the normalization factor is greater than the rate of decline of the secondary field. At very large values of coil separation the rates of decline of the primary coupling and of the secondary field will become almost equal so that the normalized output will reach a saturation value yet the normalized output of the coincident coils will continue to increase as the primary coupling of the separated coils continues to decrease. The result will be that the coincident coil response will get stronger in relation to the separated coil response regardless of the basis of evaluation; be that either the absolute secondary fields or the normalized dimensionless output.

Complex space plots of the coincident coil peak anomalies for the same ranges of depths and frequencies used in the modeling of the separated coil responses are shown in Figure 5. As in the case of the separated coil responses for the plate when located in the resistive environment in Figure 2, the response, shows a loss of amplitude at high frequency (i.e., the curl back towards the origin as frequency increases beyond 100 kHz). In this case, the effect can only be ascribed to the onset of thick conductor behaviour because the type of pull up effect seen over shallow thin targets with separated coils, does not occur when the observation point is coincident with the coils as is the case with coincident coils. This was confirmed by the study provided by Duckworth and Krebes (1998) which used a simplified theoretical model to evaluate the coincident coil concept. Thick conductor behaviour is seen in Figure 4 in the double peaked quadrature component profiles for the free-space case at the higher frequencies. This development of a double peak due to the thickness of the target, causes an apparent loss of anomaly magnitude if the sampling point for the anomaly is located at the centre of the anomaly and hence is located on the minimum which develops between the two peaks.

The complex space plots for the case when the conductive host is present in Figure 5, show a loss of amplitude with respect to the corresponding free-space response for frequencies up to 40 kHz for all target depths. This contrasts with the responses of the separated horizontal coils when the host is present which in Figure 2, show an increase of amplitude for all frequencies and all depths. Above 40 kHz the coincident coil responses in Figure 5 show enhancement and the development of a second dispersion for the deeper targets. However, in relation to the strength of the target responses in free-space, the second dispersion when the host is present, is much smaller than it is in the case for the separated coil responses of Figure 2. For the smallest target depth of 2 cm, only the onset of the second dispersion is seen. It is also notable that the onset of the second dispersion begins at different frequencies depending on target depth in Figure 5. For instance at the shallowest depth of 2 cm, the onset of the second dispersion appears to be at 200 kHz while at the depth of 5 cm it can be seen to start at 40 kHz. When the conductive host is present there is an anti-clockwise phase rotation (i.e., phase lead) for all frequencies. This anti-clockwise phase rotation can not be ascribed to the screening effects of the host in the manner of the screening caused by a conductive overburden. This can be appreciated because the predominant effect of an overburden on coincident coil responses, has been found by Duckworth and Krebes (1998) to be a clockwise phase rotation (i.e., phase delay). Studies of the separated horizontal coplanar coils when operated over targets located below a conductive overburden [Lowrie and West (1965), Hanneson and West (1984)] also found that an overburden causes a general phase delay rather than an advance as seen in Figures 2 and 5.

The response of the host separate from the targets, as detected by the separated horizontal coplanar coils for a depth to the host of 2 cm and a coil separation of 20 cm is presented in Figure 6(a). The corresponding response of the host alone as detected by the vertical coincident coils is presented in Figure 6(b). These illustrations show that response from the host alone is only detectable at frequencies above 40 kHz. This indicates that appreciable current flow within the host did not develop until that frequency range was reached. Consequently, all responses observed below 40 kHz with the target conductor in place probably involved negligible gathering of current yet the phase advance seen in that frequency range is indicative of current gathering. It is also notable that the effects seen below 40 kHz were stronger for the coincident coils in Figure 5 than for the separated coils in Figure 2 but that in this frequency range the coincident coils gave an attenuated response while the separated coils gave an enhanced response.

Discussion

In any study that is based upon physical scale modeling, it is possible that the recorded responses are in part, the result of signal paths other than the path provided by electromagnetic induction. Capacitance between the transmitter and receiver coils can provide an unwanted signal path but this is normally eliminated by shielding the coils. In the equipment employed in this study, the coils were shielded. The effectiveness of this shielding has been demonstrated in earlier studies of conductors located in a free-space environment, where the system provided results that were in good quantitative agreement with theory. Thus we anticipated that capacitative linkage between the coils would not be significant in the present study. However, a possible interpretation of the small but consistent differences between the free-space and conductive host responses of the target, seen for frequencies below 40 kHz in Figures 2, 3 and 5, is that these differences are the result of a process other than electromagnetic induction. If this is the case, then it is only the effects seen above 40 kHz that are due to current gathering. This view allows the development of the second or high frequency dispersion to be seen as being caused by the development of significant induced current in the conductive host.

If however the effects seen below 40 kHz are in fact due to the gathering into the target of weak currents induced into the host, then it becomes necessary to explain how the induction and current gathering process can undergo a marked transition at a frequency which appears to depend only on the conductivity of the host medium. It also becomes necessary to explain how the weak current gathering effect below 40 kHz can act to attenuate the responses provided by the vertical coincident coils and enhance the responses of that same coil system above 40 kHz. The fact that in all the cases treated in this study, the effects seen below 40 kHz show a phase lead such as has been shown to be characteristic of current gathering in studies published by other authors for low host conductivities, suggests that current gathering was in fact operating below 40 kHz.

Of the two interpretations presented above, the one involving stray signal would be contained by the present understanding of the physics involved. The alternative interpretation which suggests that current gathering operates throughout the whole frequency range but with a sharp onset of very strong current gathering at a particular frequency, appears to require that a new component be added to our understanding of the physics of the induction process. Such a change in our understanding would be comparable in importance to the recognition of the current gathering effect itself.

One approach to establishing which of the two explanations given above is correct, will be to repeat the whole physical model study using field sensors that are not coils. It would be unproductive to repeat the tests with different coils if the stray paths are inherent in the use of coils. Alternatively an attempt could be made to use theory to treat the same modeling conditions employed in this study but published studies based upon theoretical models indicate that the conditions employed in the physical model results presented here can not be treated by theoretical models. The development of the physical modeling system will take some time and rather than wait for the results of that work, we believe that the unusual responses provided by the present study should be made available to the exploration community now. This will possibly providing a topic of interest to people working on the development of theory who may now have approaches that can treat the conditions of this physical model study. It is also possible that the present results will provide an explanation for effects that have been observed in field surveys that have not been amenable to conventional interpretation.

Even if it is eventually shown that the effects seen below 40 kHz in the physical model results with the conductive host in place are an artifact of the modeling system, the second dispersion observed at high frequency appears to be a valid manifestation of the current gathering phenomenon. It also appears that effects of this type may occur quite commonly in full scale exploration surveys.

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