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THE INFLUENCE OF NORMALIZATION ON THE PERFORMANCE OF HORIZONTAL COPLANAR COIL ELECTROMAGNETIC PROSPECTING SYSTEMS

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ABSTRACT

An examination of the coupling of moving source electromagnetic prospecting systems to a steeply dipping high conductance plate type of target by detailed mapping of the response versus coil separation indicates that the strongest secondary field will be detected with a coil separation equal to 1.64 times the depth to this type of target. This study also indicates that the detected secondary field retains its strength for coil separation ranging from 1.64 times the target depth to zero. It is proposed that this strength of the secondary field for small coil separations indicates that short, rigid-beam EM systems in which the primary coupling between the coils can be controlled are potentially capable of providing depths of exploration comparable with those offered by widely separated coils provided that the detected secondary field effects are presented either as absolute magnitude of the secondary field or as variations of the impedance of the instrument.

INTRODUCTION

In maximum coupled frequency-domain electromagnetic systems, secondary field magnitudes are, by convention, recorded in dimensionless form by normalization with respect to the primary field. This dimensionless form of data presentation has the merit that it allows the output of systems of widely different power to be identical for identical coil separation. It also has the merit of causing the output of any device to be unaffected by changes in the output power of the transmitter. However, a less desirable aspect of the use of primary normalization is that it prevents any evaluation of the absolute magnitudes of detected secondary fields, yet in the use of moving source devices it is desirable that a knowledge of the coil separation that provides maximum absolute coupling to a conductor be appreciated. To this end, this discussion details an examination of the absolute coupling of a horizontal coplanar coil system to a steeply dipping plate type of target.

In order to determine the coil separation which will give the maximum detectable secondary field for a particular target type it would be desirable to develop an analytic function relating coil separation to absolute magnitude of secondary field. Regrettably, the development of such a function for a realistic target such as a thin plate does not appear to be a tractable problem. Alternatively, we may examine the behaviour of the response of a moving source device to a steeply dipping plate type of conductor for a wide range of coil separations by forward modelling and thereby search out the coil separation which produces maximum response. Such a search requires that the incremental change of the coil separation be small, so that such a study will involve the evaluation of a large number of anomaly profiles which will be most conveniently presented in map form. A mapping of this type will of course also involve a considerable computation burden if some of the more recently developed numerical methods are employed, such as have been described by Lee et al. (1981), Weidelt (1983), Hanneson and West (1984), Wannamaker et al. (1984) and Best et al. (1985). However, in that the aim of the search is to demonstrate the best coil separation over a reasonably realistic target while at the same time bringing the computational burden within reasonable bounds it appears acceptable that this study be conducted with a theoretical model which can be treated by a computationally undemanding algorithm. These requirements are met very satisfactorily by the theory for the response of a thin perfectly conducting plate described by Wesley (1958). The analytic expression describing the response of such a plate is readily programmed for use on PC level computers as described by Duckworth and Krebes (1995).

THEORETICAL MODELLING

The results of computing the response of horizontal coplanar coil systems to a perfectly conductive plate are shown in Figure 1c as detailed maps presented in the conventionally normalized form and in Figure 1d as absolute magnitude of the secondary field. The plate was dipping at 80° and located at a depth d. The coil separations ranged from 0 to 9d in separation increments of 0.05d with a traverse length equal to 12d in station increments of 0.05d (i.e., 180 traverses with a total of 43 200 stations). Selected profiles are shown in normalized form in Figure 1a and in absolute form in Figure 1b. It should be noted that the vertical scale in Figure 1b is arbitrary, as the only intention of the illustration is that the

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relative magnitudes of the absolute responses for various coil separations be appreciated. No attempt was made to calculate field strength magnitudes in nanoteslas as this would not be relevant to the argument. The locations of the selected profiles are emphasized on the maps. The transformation between the absolute responses presented in Figures 1b and 1d and the normalized responses of Figures 1a and 1c is achieved by multiplying the absolute responses by the cube of the appropriate coil separation.

A familiar aspect of the behaviour of the output of moving source horizontal coplanar coil electromagnetic prospecting systems when presented in the conventional dimensionless form is that their response to steeply dipping tabular conductors increases progressively as coil separation increases, as shown in Figures 1a and 1c. This leads to the natural conclusion that larger separations are to be preferred. However, the same data presented in absolute form in Figures 1b and 1d indicates that this appearance of progressive increase does not correspond to the variation of the actual secondary field that would be detected by horizontal coplanar coils with such an increase of separation. In particular, it reveals that the normalized form of data does not permit the notably strong secondary fields that reach the receiver when the coil separation is less than twice the depth to the target to be appreciated.

A notable feature of the absolute form of data presentation of Figure 1d is that it produces a strong focus when the coil separation is equal to 1.64d (i.e., d = 0.61L), this being the coil separation that provides the strongest possible secondary field from this perfectly conductive type of target, but physical modelling results discussed below establish that this relationship also holds for a target of finite conductivity.

A rule of thumb in use with moving source EM systems is that a target located at a depth equal to half the coil separation (d = 0.5L) is only marginally detectable, so that one located at the greater depth of 0.61L is effectively undetectable despite the fact that, paradoxically, that target would provide the strongest possible secondary field. Thus, it might appear that there would be merit in selecting coil separations of the order of 0.61d but this would be futile in any system in which the coils are carried as separate units because the coupling noise in such a system would overwhelm the secondary signal. This problem could be overcome by mounting the coils on a rigid beam but, of course, for a target at a depth of 100 m this would mean a beam of 164-m length which is entirely impractical. However, Figures 1b and 1d show that for coil separation ranging down from 1.64d to 0 the maximum excursion from the positive peak to the negative trough of the absolute anomaly remains essentially constant. Thus, a much smaller coil separation could be used without any loss of the absolute magnitude of the detected secondary field. In fact it can be argued that the ideal coil separation is zero as discussed by Duckworth et al. (1993). The strength of the secondary field in the coil separation range from 0 to 1.64d suggests that the beam could be reduced to a length that could be carried by a single person and still retain the ability to detect deep targets, but only if the recorded secondary field was presented in absolute form. Of course, a number of ground-borne systems mounted on short rigid beams already exist. However, these systems are inevitably viewed as shallow exploration devices – regardless of the coil orientation they employ – because of the small coil separations involved, yet this is true only because their output is usually presented in the normalized form which inevitably becomes weaker for smaller separations. The perception that depth of exploration is controlled by coil separation is an artifact of the conventional, but by no means mandatory, normalization with respect to primary coupling. In that the rigid beam concept provides a freedom from the need to express the output in normalized form, the use of the conventional form of normalization appears to be a waste of the potential capabilities of rigid-beam devices.

Perhaps the most desirable feature of rigid-beam ground-borne systems portable by one person would be the potential for low operating cost. In mountainous survey areas a short rigid-beam type of system would have the additional merit of not suffering from decoupling noise due to the terrain and could possibly be operated without cut lines. A short-beam device would make it practical for the operator to maintain the beam parallel to the local surface along a traverse and thereby generate responses from targets which would be little different than if those targets were located below a plane surface. This is a technique often recommended in the application of widely separated coils but which becomes difficult when the operators lose sight of each other due to intervening topography and are thereby unable to determine at what angle each should set their coil.

Small coil separation could also provide an additional benefit in that it would display a greater ability to resolve the anomalies due to closely spaced target conductors as demonstrated by Duckworth and O'Neill (1992). An additional merit would be the ability to employ the device in a variety of orientations such as broadside horizontal coplanar (Jain, 1973) or broadside vertical coplanar to take advantage of the interpretation opportunities that different coil orientations offer. In this context, the ease with which a short-beam device could be used in the broadside mode of operation would permit a very immediate method for determining target depth from the geometry of the profile in a manner similar to that described by Duckworth et al. (1991).

It can be argued that presenting the output of a moving source system in absolute form will make the responses dependent on transmitter power so that any changes in this power will generate spurious anomalies. However, this could be avoided while retaining the characteristics of the absolute form of readout if the response was presented as impedance i.e., receiver coil voltage divided by the transmitter current (rather than being divided by the primary voltage) as is done in the readout provided by some TEM systems. However, this impedance form of readout would not permit different devices of widely differing transmitter power to give identical results, although this disadvantage could be overcome by calibrating devices over a standard target. Thus, this

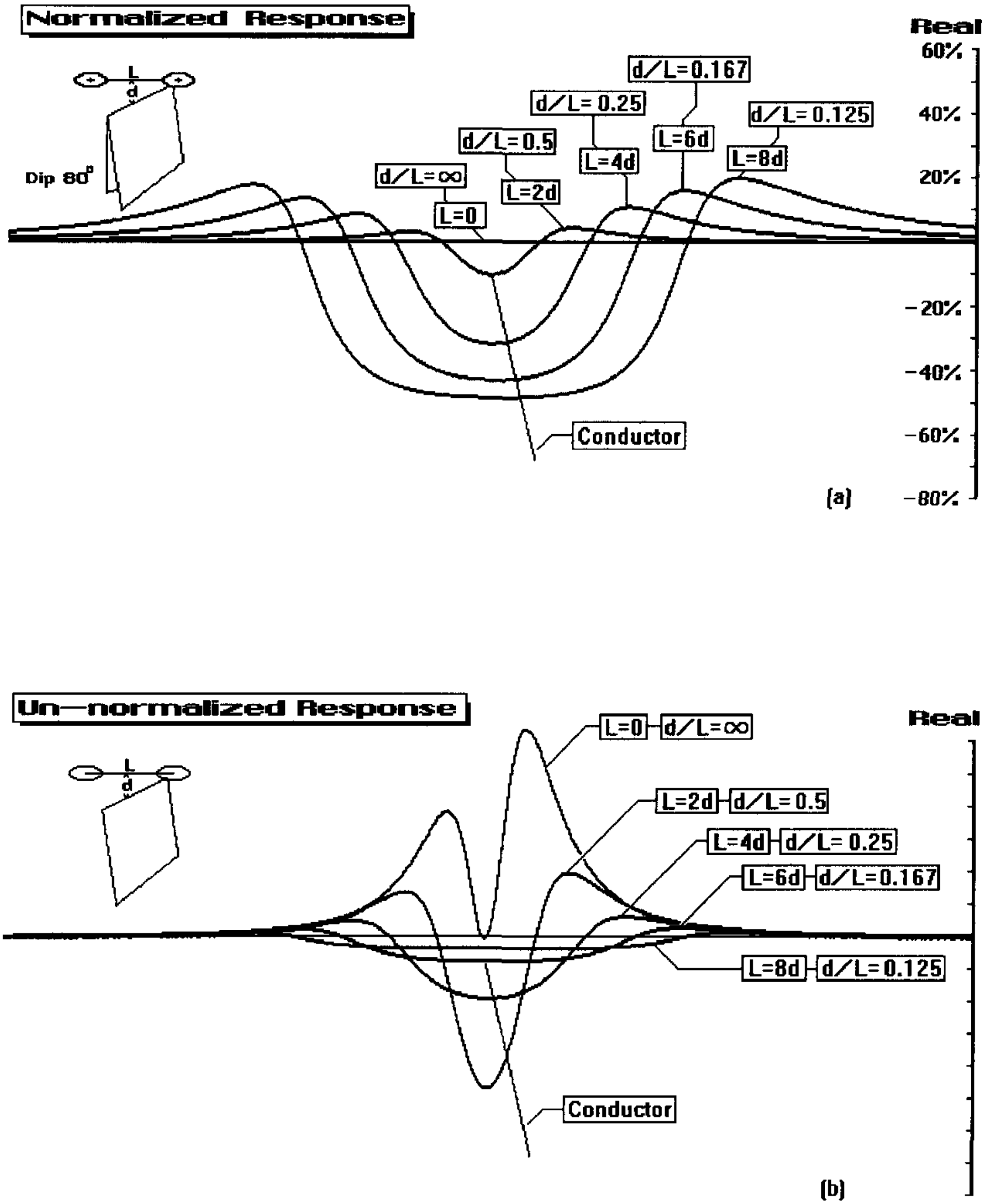
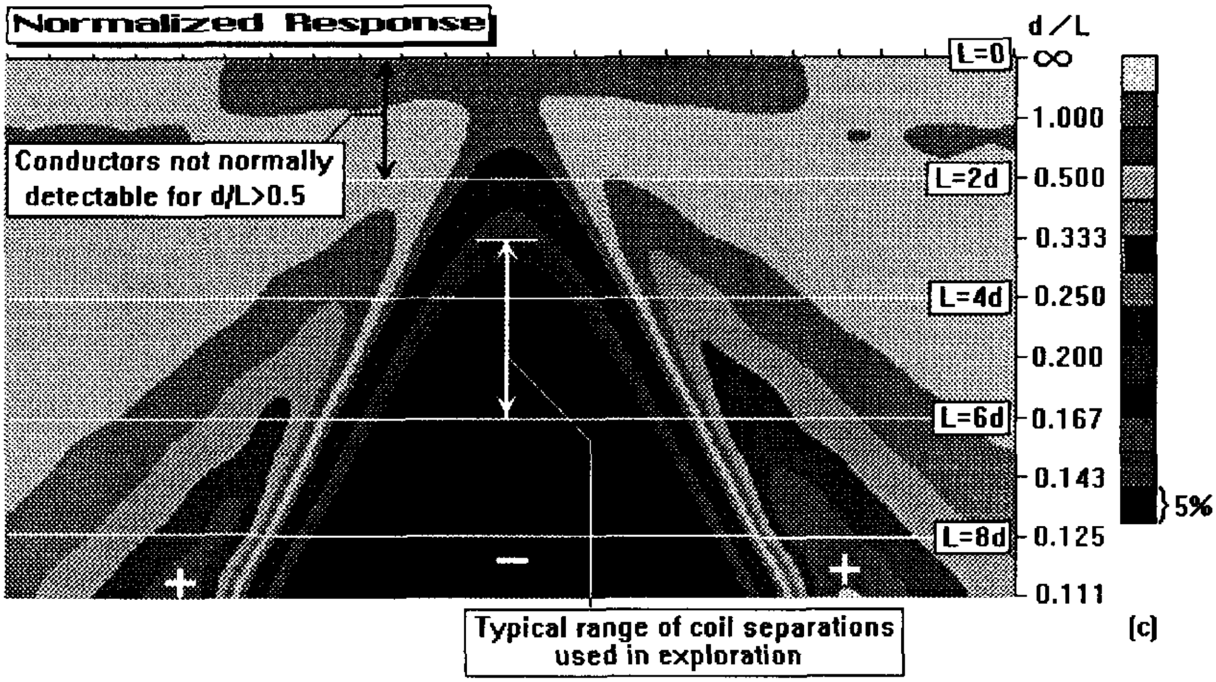


Fig. 1. **(a)** Normalized theoretical response to a horizontal coplanar coil system of a thin perfectly conducting tabular conductor dipping at 80°. **(b)** Absolute response of the same conductor (NB: the vertical scale is arbitrary, as the only intention is to demonstrate the relative magnitudes of the absolute responses).



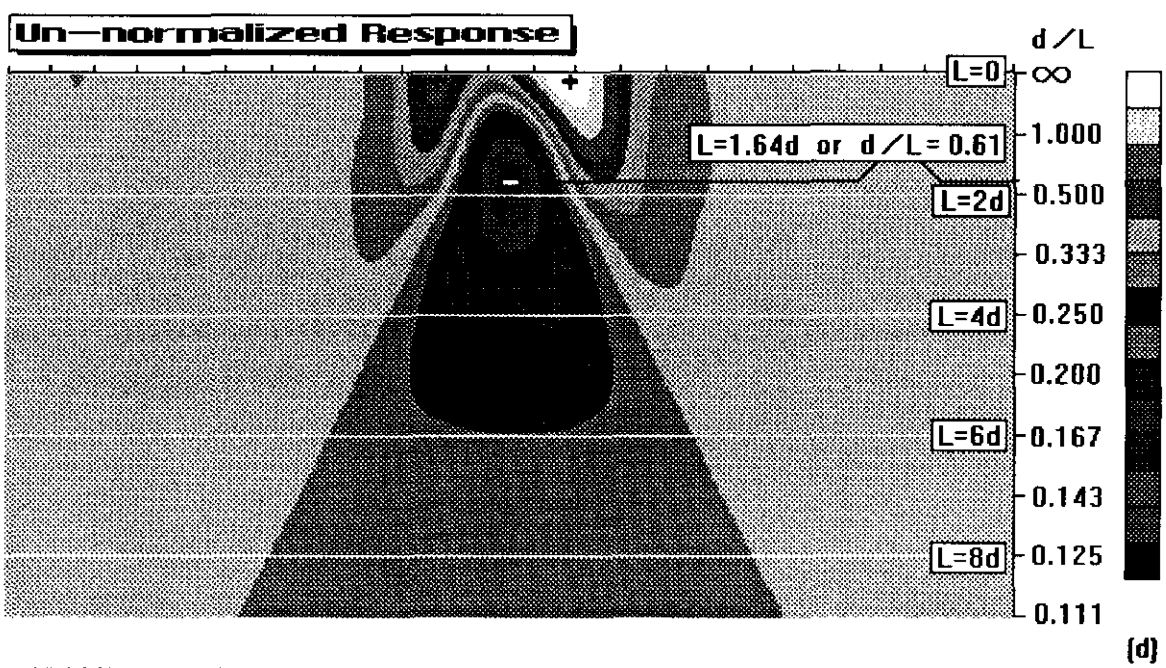


Fig. 1. (Cont'd) **(c)** Normalized theoretical response to a horizontal coplanar coil system of a thin perfectly conducting tabular conductor dipping at 80° in map form as a function of depth-to-separation ratio. **(d)** Absolute response of the same conductor showing the focussing of the response for a depth-to-separation ratio of 0.61.

normalization with respect to the primary current would allow the device to retain one of the desirable features of the conventional form of normalization, i.e., freedom from effects due to variation of the transmitter power in any one device, while allowing the readout to reflect the true variations of the detected secondary fields that is not provided by the conventionally normalized form of readout.

An intriguing possibility is suggested by Figure 1d: if coil separation and coil orientation could be controlled with sufficient precision then an immediate advantage of an absolute (or impedance) form of output would be that depth to the target could be determined by an expansion of the coil system, as in Figure 1b, to find the coil separation at which the central negative anomaly becomes maximum. Of course, such a variation of coil separation while maintaining very precise control over the separation and orientation of the coils is impractical. However, a similar result can be achieved by processing the response obtained with a single fixed coil separation as described by Duckworth and Krebes (1994).

The dipole type of coil assumed throughout this discussion (and employed in Wesley's algorithm) is, in effect, a coil of vanishingly small dimensions. A rule of thumb for real coils that is commonly employed is that the dipole field approximation does not hold if the point of observation is located less than about 5 coil diameters from a real coil. This causes the concept of small coil separation to be viewed as approaching and possibly violating the 5-coil-diameter rule. Indeed, the signal recorded by a real coil of finite size placed close to a transmitter of finite size will differ from that predicted by dipole theory. However, this is not the inductive relationship which is important; it is the relationship of the coils to the target that is of greatest importance and if the target is located at a depth greater than 5 coil diameters then the response of the target will be accurately predicted by dipole theory. It is unlikely that in a full-scale survey a target conductor will ever be located at a depth of less than 5 coil diameters, although this can happen in physical modelling. In the following example of the comparison of responses generated by means of perfect conductor theory and data acquired by means of physical modelling, the depth of the model conductor at 6 cm was less than the 5-coil-diameter rule because the model coils had a diameter of 1.5 cm yet the two sets of data show very good agreement. This suggests that the 5-coil-diameter rule is perhaps too conservative.

Physical Modelling

To confirm that the behaviour of these responses shown in Figure 1 is not a physically unrealistic artifact of the theoretical model or of our implementation of that model in software, we examined the response of a thin vertically dipping high conductance tabular target by means of scale modelling. The results of this test are presented in Figure 2a, while the corresponding perfect conductor theoretical responses are shown in Figure 2b. The target was maintained at a depth of 6 cm while the coil separation was increased in steps of 2 cm from 4 cm to 26 cm. The imaginary component responses from the scale model are not presented as these do not relate to the output of the theoretical perfect conductor model. The target was chosen to correspond as closely to the perfect conductor case as possible (the target was an aluminum plate of 0.8 mm thickness with a conductance of approximately 32 000 S) so that the imaginary response was almost zero. In fact, the model system was not capable of reliably measuring the imaginary magnitudes at the very low level achieved in this experiment. In Figures 2a and 2b the upper set of profiles are in the absolute form while the lower set are in the conventionally normalized form. In the scale model it was not possible to take the separation of the coils to zero, so that the theoretical responses are presented for the same separations as in the scale-model responses even though smaller separations could have been treated in the theoretical model. It is clear that the scale-model data agrees very well with the theoretical data in all respects. It should be noted that the scale-model data show the strongest central negative anomaly in the unnormalized profiles for a coil separation of 10 cm, which for the target depth of 6 cm indicates an optimum depth-to-separation ratio of 0.6 which is in very good agreement with the 0.61 ratio indicated by the perfect conductor theory. In comparing the absolute profiles with the normalized profiles it should be appreciated that the profiles for 4-cm coil separations have such small amplitude in the normalized form that they merge with the baseline and can not be seen.

Conclusions

In the type of moving source electromagnetic systems where each coil is carried by a separate operator, the lower sensitivity to orientation error that large coil separation provides is clearly preferable to the difficulties that smaller separations would present even though such smaller separations could provide significantly stronger coupling to the steeply dipping type of target. However, in a system where the coils are rigidly mounted on the same beam, the only constraint to reduction of the coil separation lies in the noise inherent to the electronic system and the rigidity of the beam. If in such rigid-beam systems the practice of normalizing the output with respect to the primary coupling was abandoned in favour of normalization with respect to the transmitter current then these devices would not be inherently limited in their depth of exploration just because of their small coil separation. In fact, these devices would be able to take advantage of the notably strong coupling to steeply dipping targets that is available for the depth-to-separation range from ∞ to 0.61L. This alternative form of normalization would provide the same freedom from transmitter power variations that the conventional normalization provides while preserving the benefits of an absolute form of data presentation. As this alternative form of normalization would not be dimensionless, the output of different devices would differ depending on the characteristics of the coils employed, so that comparisons between devices would require their performance over a common standard conductor to be recorded in order to

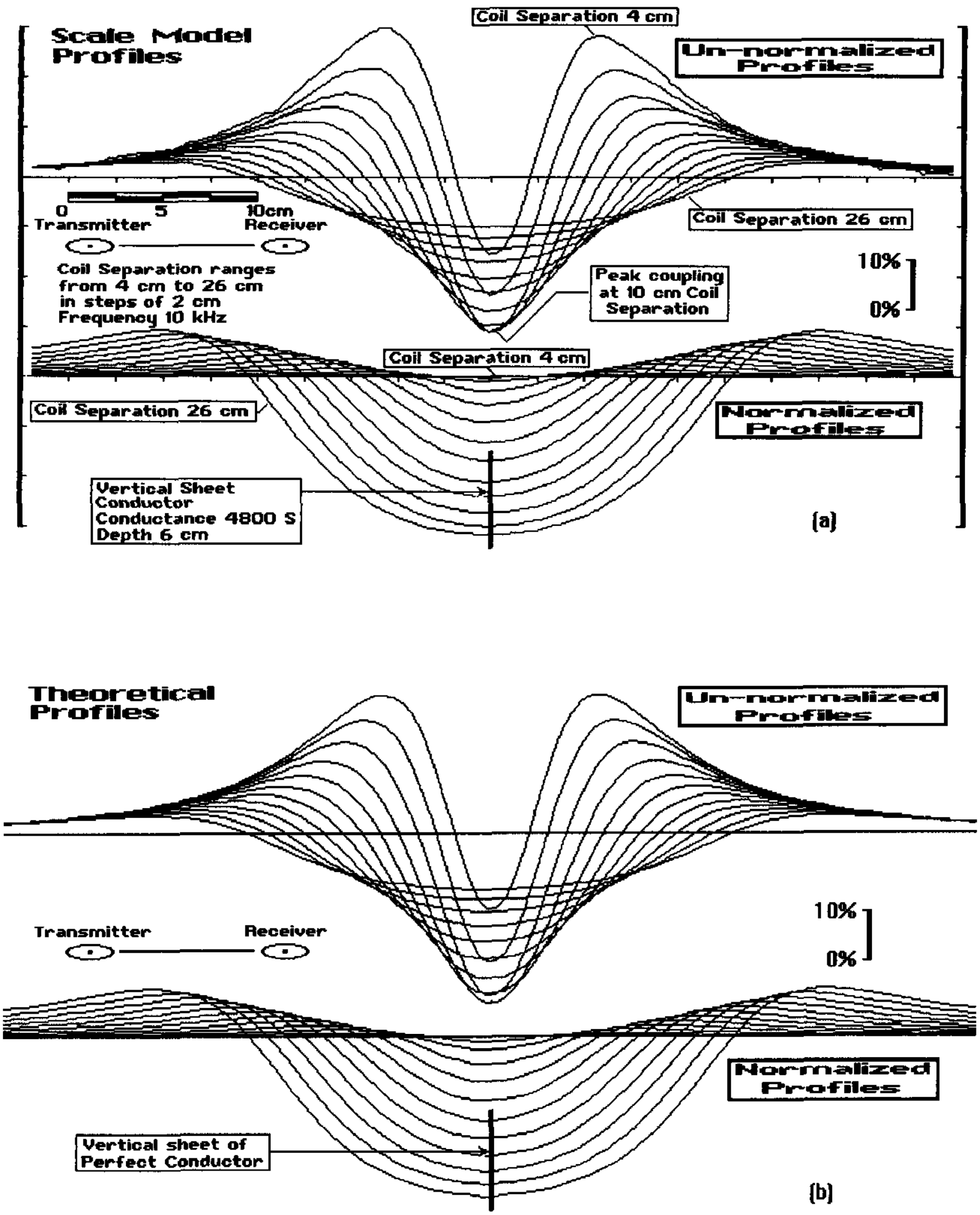


Fig. 2. (a) Scale-model real-component profiles obtained with a horizontal coplanar coil system over a high conductance thin vertical conductor for a range of coil separations. The upper and lower sets of profiles are the same data presented in the absolute and conventionally normalized form. Note that the peak negative anomaly in the absolute form of presentation occurs for a depth-to-separation ratio of 0.6. **(b)** Theoretical real-component profiles for a horizontal coplanar coil system over a thin perfectly conductive vertical conductor for the same range of coil separations employed in the scale-model responses of Figure 2a.

calibrate the readout of each device, but this is a common practice in the use of many other geophysical devices. This appears to be a small disadvantage in return for the potential benefits of this concept. There appears to be no reason why rigid-beam devices could not be designed with the option to switch between the two types of normalization in order that direct comparisons of the merits of the two forms of data output could be available to the operator.

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