EM Induction in Elongated Conductors Normal to a Coastline with Application to Geomagnetic Measurements in Nigeria

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Magnetic induction responses of elongated pairs and single conductors with strikes perpendicular to a local coastline of a deep ocean are studied with the aid of laboratory model measurements. The dependence on period, the width of the conductor, and the distance from the end of the conductors are examined for traverses over the conductors. It is shown that for the model geometry studied, the ocean induction effects can be subtracted to yield the Parkinson induction arrows for the conductor alone. At sites between pairs of parallel conductors the quadrature arrows compared with the in-phase arrows show a very differing period dependence. These results have particular application to the interpretation of geomagnetic measurements at sites between major elongated conductive structures such as sediment filled grabens.

1. Introduction

Electromagnetic responses of anomalous conductors continues to be a topic of interest in geomagnetic studies. A sediment filled graben with significant fluid content would be an example of a conductive body that could be expected to exhibit a significant electromagnetic response. If situated near an ocean, the response of such a graben would be expected to be partially masked by the coast effect response. Removing the unwanted ocean induction components by subtracting numerically calculated, or analogue modelled coast effect induction arrows before interpretation has been studied by Wolf (1983), Weaver and Agarwal (1991), Dosso and Meng (1992), Chen (1994), Kang (1995), and Chen and Dosso (1997). The numerical model method, using thin sheet modelling, has been used by Bapat et al. (1993) and Chamalaun and McKnight (1993) in geomagnetic surveys in Japan and New Zealand respectively, while the analogue model method of accounting for the coast effect has been applied to measurements at sites in coastal regions of North China (Meng et al., 1990), Japan (Meng and Dosso, 1990), New Zealand (Chen et al., 1993, Dosso et al., 1996a, b), and Northwest Nigeria (Kang et al., 1993).

In a recent work, Chen and Dosso (1997) have used analogue models to study the response of elongated conductors with strikes parallel to an ocean coastline. They examined the dependence on period, the distance from the ocean, and the depth extent of the horizontal elongated conductors and also showed that the ocean effect could be successfully subtracted to yield the responses of the elongated conductor alone for conductors located as distances as small as 50 km from the coast. These results have particular application to geomagnetic measurements in the New Zealand South Island where a reasonable premise is that of an elongated conductive zone (Chen et al., 1993) being associated with the Alpine Fault system some 50-100 km inland, and roughly parallel to the coastlines.

In the present work the case of elongated pairs and single conductors with strikes perpendicular to a local ocean coastline are studied using laboratory analogue models. The responses along traverses perpendicular to the strikes of the conductors for a range of distances from the ends of the conductors nearest the ocean, as well as the subtraction of the ocean effect responses, are examined. For the present

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model geometry, the responses of these elongated conductors are not simply those of two-dimensional models, and thus analogue modelling where three-dimensional models are readily treated, appears most appropriate.

2. The Laboratory Analogue Models

Figure 1 shows the schematic plan view of a model of a pair of elongated conductors with strikes perpendicular to a straight coastline of an ocean simulated in the laboratory. The elongated conductors are at the surface of a uniform host earth, with both the host earth and the ocean underlain by a conductive substratum at a depth of 200 km. In the laboratory analogue model, graphite plate was used to simulate the 5 km depth ocean, the elongated conductors, and the conductive substratum, while concentrated brine in a large wooden modelling tank simulated the host earth. It should be noted that in the model the elongated conductors are not in contact with the deep ocean, but are truncated just short of the coastline. The modelling facility, including the measuring equipment and the overhead uniform field source, used in a wide range of previous EM induction studies at the University of Victoria, and is not described here. The details on the modelling facility are available in the early work of Dosso (1973). In the present work, the length and frequency scaling factors were chosen so that for example, 1 mm and 100 kHz in the laboratory model simulated 1 km and 5 min period respectively in the geophysical system. The ocean depth and the conductor lengths were modelled to be 5 km and 500 km respectively. The laboratory model in-phase and quadrature (out of phase) magnetic field components at simulated periods of 1–90 min were measured for $X$-polarization (inducing magnetic field in the $Y$-direction) for traverses in the $Y$-direction, perpendicular to the strikes of the parallel conductors, and for the models that included the ocean, both

![Diagram of a model of a pair of elongated conductors](image)

**Fig. 1.** Plan view of a model of a pair of elongated conductors (embedded in the host earth) perpendicular to a straight coastline. The width $W_a = 5$ km and the separation distance $S = 50$ km are held constant while $W_b$ is varied.
$X$- and $Y$-polarizations parallel and perpendicular to the coastline. The magnetic field components measured along the traverse were used to obtain the well-known Parkinson induction arrows, both in-phase (real) and quadrature (imaginary), with the signs of both reversed following the convention of Lilley and Arora (1982) for time varying field of the form $e^{i \omega t}$.

3. Discussion of the Analogue Model Results

Figure 2 shows the in-phase (real) and quadrature (imaginary) Parkinson induction arrow components along a traverse (T2 in the $Y$-direction) that is 30 km ($X = 30$ km) from the ends of the conductors.

![Figure 2](image-url)

Fig. 2. The in-phase and quadrature $V_y$ ($y$-component of the induction arrow response of the pair of conductors) and $D_y$ ($y$-component of the response of the ocean and conductors minus the response of the ocean) for traverse T2 over the model of a pair of elongated conductors perpendicular to the straight coastline for $W_a = 5$ km and $W_b = 20$ km.
nearest the ocean. In this figure, as well as in others that follow, the magnitude of the curve at a given point Y represents the length of the arrow, while the sign indicates the direction, to the right if positive, and to the left if negative. Further, the elongated conductors are 5 km thick, and measurements are carried out for various conductor widths \((W_a, W_b)\) and conductor separation distances \((S)\). In Fig. 2, the solid-line curves give the induction responses \(V_y\) (the responses of the elongated conductors without the ocean), while the dashed-line curves give the difference induction response \(D_y\) (the responses of the model ocean alone subtracted from the responses of the model of the ocean and the conductors together). A significant point to note is that the solid and dashed lines are essentially the same, even at the shortest periods. Measurements were also made for traverses along \(X = 10\ km\) and \(250\ km\), with similar good agreement between the \(V_y\) and \(D_y\) response curves, confirming negligible electromagnetic mutual coupling between the ocean and the elongated conductors, as would be expected for the present model geometry in which the strikes are perpendicular to the ocean coastline, and the conductors are not in physical contact with the deep ocean. This result demonstrates that for the case of elongated onland conductors with strikes perpendicular to an ocean coastline the geomagnetic coast effect can be subtracted from geomagnetic measurements to yield the induction responses of the conductors alone. The response curves also show that except for differences in sign, the responses to the right of the narrow \((W_a = 5\ km)\), and to the left of the wide \((W_b = 20\ km)\) conductor are roughly the same at each period, with the in-phase responses decreasing with increasing period and the quadrature responses, first showing response maxima at 3 to 5 min, and then also decreasing gradually with increasing period. Similar behaviour was also noted for traverses (not shown here) at \(X = 10\ km\) and \(250\ km\), but with responses at each period approximately a factor of 2 smaller for \(X = 10\ km\), and a factor of 2 larger for \(X = 250\ km\), than for the traverse shown in Fig. 2. Thus, it can be concluded that for geomagnetic measurements over an elongated conductor of length studied here, the distance from the central region of the conductor would play an important role in the observed response, as would be expected for a 3D structure.

In the region between the two conductors in Fig. 2 the in-phase response, negative at sites near conductor \(b\), is reversed in sign to be positive at sites near conductor \(a\), and zero at some intermediate site. The location for zero response is seen to shift towards the narrow conductor \(a\) with increasing period. The behaviour of the quadrature response (particularly at short periods) at sites between the conductors is somewhat more complex than that of the in-phase response, showing the effects of both edges of the wide conductor \(b\). Further, the site for zero-response in general differs somewhat from that for the in-phase response. However, the fact that the two components at a given site reverse directions at slightly different periods would have rather limited importance in any interpretation of geomagnetic measurements since the responses near those periods are so small.

Figure 3 demonstrates further the responses as a function of period at sites between parallel conductors, showing the response maximum \(V_m\) for conductors \(a\) and \(b\) for 3 traverses, for a range of conductor widths \(W_b\) and for conductor separation distance \(S = 50\ km\). Showing the three dimensional effect, the responses are seen to be the largest for the traverse \((T3)\) over the central region of the 500 km long conductors, and decreased for traverses \((T2\ and\ T1)\) nearer the ends of the conductors. At a given period, increasing the width of conductor \(b\) has the effect of decreasing the response of the fixed width conductor \(a\) and increasing the response of the wide conductor \(b\). The in-phase responses for all traverses decrease rapidly with increasing period, showing negligible values at periods greater than about 20 min.

The quadrature responses in Fig. 3 are seen to be more complex than is the case for the in-phase responses. The curves show a distinct maximum for each conductor at a period which increases somewhat with distance from the end of the conductor. For example, at 10 km \((T1)\) from the end for conductor separation distance \(S = 50\ km\), the maximum in the responses occurs at roughly 3 min, while for the central profile \((T3)\) they occur at 5 to 6 min. The responses are generally larger for conductor \(b\) (the wider conductor) than for conductor \(a\), with the responses in the region of the maxima for \(b\), increasing with conductor width \((W_b)\). It is also interesting to note that, the in-phase \(V_m\) value (Fig. 3) at the period for quadrature \(V_m\) maximum, is roughly the same as the quadrature \(V_m\) value. For example, for \(T3\), and \(W_b = 5\ km\) (curve 1), the quadrature and the in-phase values are each roughly 0.4. The fact that the conductors
Fig. 3. Empirical curves of the in-phase and quadrature maximum $V_m$ response as a function of period for traverses $T_1$, $T_2$, $T_3$ over the model of a pair of elongated conductors for $W_a = 5$ km and $W_b = 5, 10, 20, 50, 100$ km for $S = 50$ km.

$a$ and $b$ each show increased responses with increased separation distance $S = 100$ km (not shown here), is attributed to decreased electromagnetic mutual coupling between the two conductors, since in the region between the two conductors, the responses are of opposite sign, leading to a partial cancelling of responses.

Figure 4 shows the period response curves (for $S = 50$ km and 100 km) at selected sites ($-y$) between the pair of parallel conductors for the model in Fig. 2. The responses at $y = -5$ km are generally larger for $S = 100$ km than for $S = 50$ km as would be expected due to decreased mutual inductive coupling for the larger separation distance. At sites ($y = -5$ and $-10$ km, and $y = -5$ and $y = -15$ km) near the narrow conductor the in-phase and quadrature responses have significant magnitude and are positive at all
Fig. 4. Empirical curves of the in-phase and quadrature responses $V$ as a function of period at selected sites ($-Y$) between the elongated parallel conductors for conductor separation distances $S = 50 \text{ km}$ and $100 \text{ km}$.

periods, while at sites ($Y = -40$ and $-45 \text{ km}$, and $Y = -85$ and $-95 \text{ km}$) near the wide conductor the responses are negative at all periods, with the responses in the transition region ($Y = -20$ to $-30 \text{ km}$ for $S = 50 \text{ km}$, and $Y = -40$ to $-60 \text{ km}$ for $S = 100 \text{ km}$) being very small. Further, at the very short periods up to about 3 min the in-phase responses are at least a factor of two larger than the quadrature responses. Over this period range the in-phase responses are decreasing and the quadrature responses are increasing, so that in the neighbourhood of 4 to 5 min the two responses are roughly equal. With further increase in the period the
quadrature response becomes the larger by approximately a factor of two at 10 min, and by even a larger factor at longer periods. Thus, for a pair of parallel elongated conductors, it would be expected that at any given site between the conductors, except in the central transition region where the responses are negligibly small, the in-phase and quadrature arrows would have the same direction, with the in-phase arrow the larger at short periods and the quadrature arrow the larger at longer periods, and the two arrows being roughly identical at some intermediate period. It should be pointed out that in the present model the

![Graph](image-url)

**Fig. 5.** Empirical curves of the in-phase and quadrature maximum $V_m$ response as a function of period for conductor widths $W = 5, 10, 20, 50, 100$ km for traverses T1, T2, T3.
conductors have the same relatively small depth extent (5 km), and that if the depths were greater and/or not the same, other differences between the in-phase and quadrature responses would be expected, even including responses of opposite sign at some sites at some periods.

The effect of conductor width is demonstrated more fully, but for the model of a single elongated conductor, in Fig. 5. At short periods the $V_m$ responses for both the in-phase and quadrature components increase with increasing conductor width, while at the longer periods, the opposite is observed, with the period at which the transition occurs for the in-phase response shifting to longer periods for traverses nearer the end of the conductor. For example, the periods at which the transitions occur are roughly 7, 9,
14 min for traverses T3, T2, T1, respectively. In the case of the quadrature response curves, the transition occurs at roughly 20 min for each of the three traverses. Thus, it is interesting to note that at some characteristic period for a given traverse, the observed $V_m$ responses are independent of conductor width, and that these periods differ for the in-phase and quadrature responses.

The dependence on distance from the end of the conductor for a range of periods is shown in Fig. 6. At 2–5 min and 2–10 min, the in-phase and quadrature $V_m$ responses respectively increase with conductor width, while at longer periods the responses for each component decrease with conductor width, agreeing with the results in Fig. 4. Further, on this logarithmic scale for distance $X$ (km) from the conductor end, the magnitudes of the $V_m$ responses increase approximately linearly with range.

Fig. 7. The in-phase and quadrature $V_x$ and $V_y$ (x- and y-components of the induction arrow response of the conductor) and $D_x$ and $D_y$ (x- and y-components of the response of the ocean and conductor minus the response of the ocean) for traverse over the model of the elongated conductor with strike at an angle of 45° relative to the sides of a right angle coastline contour for conductor width $W = 100$ km.
Figure 7 shows the $V_x$ and the $V_y$ (x- and y-components of the induction arrow responses of the conductor), and the $D_x$ and $D_y$ (x- and y-components of the difference induction arrow responses, i.e. the response of a model ocean with the conductor minus the response of the ocean alone) for traverse T2 over a 100 km wide elongated conductor with strike 45° relative to a right angle coastline. For this conductor geometry, the x- and y-components of the induction arrow responses are expected to be roughly of equal magnitude, agreeing with the observations. The negative $V_x$ and the positive $V_y$ to the left of the conductor along T2 yield an induction arrow pointing directly towards the conductor, also as expected. The excellent agreement between the $V_x$ (and $V_y$) and the $D_x$ (and $D_y$) curves for T2 (as well as for T1 at $X = 20$ km, and T3 at $X = 90$ km, not shown here) indicates that even for such a major conductor the inductive mutual coupling is sufficiently small to permit subtraction of the ocean responses to yield the responses of conductor alone. The induction responses of this latter model, as well as those of the conductors (Figs. 2-6) with strikes perpendicular to a straight coastline, have particular application to the interpretation of geomagnetic field measurements in coastal Nigeria where major on land conductive structures tend to have strikes roughly perpendicular to the local coastline.

4. Application to Geomagnetic Measurements in Coastal Nigeria

In an earlier work Kang et al. (1993) discussed geomagnetic field site results and analogue model measurements at 11 sites in south-west Nigeria. Analogue model ocean effect responses were subtracted from the field site responses to yield induction arrow responses of any anomalous conductors in the region. In that work an attempt was made to attribute the difference arrow responses at 20, 30, and 60 min to the numerous north-south striking faults in the coastal region. In a subsequent work Dosso et al. (1996a), in analyzing difference arrow responses at sites in New Zealand, concluded that a major deep fault zone such as that of the Alpine Fault could show major responses, but that most minor faults would be expected to show negligible, if any, responses. In the present work induction arrow responses have been examined at sites between pairs of relatively wide, but shallow (5 km) elongated conductors, and also the responses of single wide conductors. It was demonstrated that even for such major conductors the ocean responses could be subtracted successfully, and that the behaviour of the difference arrows was highly period and location dependent, with the quadrature and in-phase components at given periods differing from each other considerably from site to site.

Figure 8 shows the model and the field site in-phase and quadrature induction arrows at 20 min at eleven sites in Nigeria discussed previously by Kang et al. (1993). The solid and dashed arrows in Fig. 8 are the analogue model and the field site arrows respectively. The model arrows show the typical coast effect responses expected, pointing towards the ocean and decreasing in magnitude with distance from the coast. The field site results show a more complex behavior, indicating that the responses are not only those of the ocean, but a combination of the ocean and some onland anomalous conductors in the region.

The in-phase and quadrature difference arrows (field arrows minus model arrows) at 20 min at eleven sites in Nigeria are shown in Fig. 9. Differing from the earlier work, the grabens G1 (AFOWO), G2 (ORIMEDU), and G3 (ISE) which could be expected to be conductive, are now included. These grabens (Omatsoala and Adegoke, 1981), as well as the series of faults, shear zones, and the Benue Trough are attributed to the tectonic processes associated with the early opening and closing of the South Atlantic and the depositing of continental and marine sediments. The wide grabens of depths up to 6 km (Omatsoala and Adegoke, 1981) are sediment filled, and thus could be expected to provide major induction responses. Since these conductive grabens would not be expected to extend seaward beyond the continental edge, and thus not be electrically well connected to the deep ocean, the subtraction, shown to be valid for elongated conductors not connected to the deep ocean in the analogue models studied, should also be valid for the response of the grabens that at most extend beneath the shallow ocean of the Gulph of Benin.

In Fig. 9 the behaviour of the difference arrows at sites near the grabens and the Benue Trough can now be reinterpreted based on the analogue model results that the coast effect responses could be subtracted successfully to yield the responses of major (wide) conductors normal to a local coastline, both
Fig. 8. The analogue model (solid arrow) and field site (dashed arrow) in-phase and quadrature induction arrows for 11 sites in Nigeria (after Kang et al., 1993).

for a straight coastline and for a sharply curved coastline (such as the Gulf of Benin in the Benue Trough region). Secondly, it was shown that at sites between a pair of parallel conductors, the in-phase and quadrature arrows, though expected to have the same direction at any given period, their magnitudes could differ widely, with the in-phase being the larger at short periods and the quadrature being the larger at long periods.

The sites that warrant further consideration are BAD, IKD, AGB, EJI, and OKI. In the earlier work (Kang et al., 1993), the behaviour of the arrow at BAD was considered rather erratic with changing period (periods of 20, 30, 60 min), and since some measurements were known to be in error, no attempt was made to interpret the observations. However, noting that BAD is situated between a pair of grabens (G1 and G2), the fact that the in-phase response at 20 min is negligible while the quadrature response is large with the arrow pointing towards graben G1, is quite plausible, particularly when it is realized that the more distant graben G3 would also have an effect at BAD, and at 20 min the in-phase response of G1 to the west could very well be cancelled by the combined responses of G2 and G3 to the east of BAD, while the quadrature response could be showing G2 as providing the major contribution.
Both the in-phase and the quadrature arrows at IKO, the site just to the east of graben G2, would certainly be expected to point towards G2. In the earlier work, a conductor extending from the coast to F4 was postulated to account for the persistent westward pointing of both components at all periods. The very close proximity of graben G2 could readily account for such responses.

The observed responses at AGB, the site roughly midway between G2 and G3, showing short arrows pointing towards G2 at 20 min (also the case for both components at 30 min, and the quadrature at 60 min,
EM Induction in Elongated Conductors Normal to a Coastline

not shown here), could be accounted for primarily by the combined responses of G1 and G2 to the west being consistently somewhat larger than the response of G3 to the east. In the earlier work, the short arrows at AGB pointing westward were taken to again support a premise of a conductive structure to the west extending from the coast towards fault F4.

At EJI, the site just to the west of graben G3, the in-phase arrow at 20 min points directly towards the graben, while at 30 and 60 min (not shown), the arrows have rotated to point southeast, as if responding also to the Benue Trough structure. The quadrature arrow at 20 min (also at 30 min, not shown) points in a northerly direction. Site EJI is in a rather complex multiple-faulted region, where in addition to the grabens, there may be other significant conductors associated with the faults. Further, the landward extent and direction of the grabens may differ somewhat from that shown.

At site OKI, near the Benin Hinge Line (the fault structure marking the southwestern limit of the Niger Delta Basin), the in-phase arrow at 20 min, and also at 30 and 60 min (not shown), points directly towards the Benue Trough as might be expected (and as discussed earlier) in view of the deepening sediments south eastward of the Benin Hinge Line. The quadrature response at 20 min (also at 30 min) is negligible, but at 60 min (not shown) a somewhat larger arrow also points towards the Benue Trough. The response of graben G3 to the west and the Benue Trough to the southeast would clearly provide components in the observed resultant response.

The results of this present work demonstrate that even for onland large elongated conductors with strikes roughly perpendicular to a local straight or curved coastline, the ocean effect response can be subtracted to yield the responses of the elongated conductors alone. Further, at sites between parallel elongated conductors, the in-phase and quadrature induction arrows as a function of period have differing behaviour, with the magnitudes of both either decreasing or increasing with period, or one increasing and the other decreasing. Also, the responses for a traverse over the central region of the elongated conductor are significantly greater than responses at traverses near the end of the conductor. Applying the results of the model studies of the responses of parallel elongated conductors to geomagnetic measurements in coastal regions of Nigeria, the observations at a number of sites that posed some difficulty in an earlier work (Kang et al., 1993), are here more convincingly accounted for by induction in a series of onland roughly parallel sediment filled grabens.

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