Geophysical Journal of the Royal Astronomical Society, 1983, 73, 689–704.
https://doi.org/10.1111/j.1365-246X.1983.tb03340.x

A comparison of time and frequency domain geomagnetic sounding

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Summary. A three-site geomagnetic data set from the Borders region of southern Scotland is used to examine the empirical relationships established by *differential geomagnetic sounding* experiments. A *time domain* analysis of such relationships reveals time domain transfer functions which appear to be almost independent of time. A frequency domain analysis is then used to illustrate both a significant phase rotation and a significant dependence on period of the equivalent frequency domain response functions. The formalism of conventional geomagnetic sounding is re-examined. It is found that difference fields are not required to establish the appropriate horizontal field relationships.

Introduction

Time domain differential geomagnetic sounding (DGS), as defined by Babour & Mosnier (1977), is an experimental technique in which synchronized difference fields of the horizontal magnetic components are recorded between a number of mobile sites and a reference site. The extension of the technique to vertical fields is considered by Babour *et al.* (1976) and Babour (1977). We here consider only horizontal components.

The technique has been used in a large number of regions that include Britanny (Babour & Mosnier 1977), Italy (Babour & Mosnier 1977), the north-eastern Pyrenees (Babour *et al.* 1976), the south-western Pyrenees (Galdeano *et al.* 1979), Morocco (LEGSP & DMGM 1977) and in the Rhinegraben (Babour & Mosnier 1979, 1980; Albouy & Fabriol 1981). The dimensions of the areas investigated are small, typically 100 km. The basis of the technique lies in the fact that the difference field, obtained over small distances (e.g. 10 km), is a direct measure of the anomalous field at a number of sites with respect to a common reference.

All the above studies, without exception, appear to have identified the property that the anomalous horizontal field, as obtained from the difference fields, retains the same phase over the region investigated, at all variation periods. Such a property is remarkable in that when regarding magnetic field relationships derived from induced current distributions, we would normally anticipate both reactive and resistive components to be present, given a sufficiently extensive bandwidth. The empirical relationships obtained in the time domain between difference field components may be summarized:

$$H_{IR}(t) = K_I \cdot D_{IR}(t) \tag{1}$$

$$H_{IR}(t) = L_{IJ} \cdot H_{JR}(t) \tag{2}$$

$$D_{IR}(t) = M_{IJ} \cdot D_{JR}(t). \tag{3}$$

The three equations relate the observed differences in the magnetic north–south (H) and east–west (D) components between two sites I and J and a reference site R, with:

$$H_{IR}(t) = H_I(t) - H_R(t)$$

$$D_{IR}(t) = D_I(t) - D_R(t)$$

and equivalent expressions for (H_{JR}, D_{JR}). The observed time domain transfer functions (K_I, L_{IJ} and M_{IJ}) are said to be independent of time over the bandwidth of the observations. The bandwidth over which the empirical relationships hold is clearly important but is not expressed unequivocally in the time domain. Babour & Mosnier (1977) suggest the relationships are true for all time-scales covered by the studies and which appear to be 10–7200 s (Babour & Mosnier 1979).

Equation (1) expresses a linear polarization of the horizontal difference field at any site I. Equations (2) and (3) express the fact that a time-independent spatial constant of proportionality exists between the same component of the difference field referred to a common reference R. From the study undertaken in the Rhinegraben (Albouy & Fabriol 1981), equivalent relationships were obtained in the period range 1–125 s and further relationships were obtained relating electric north–south (N) and east–west (E) components:

$$N_I(t) = O_I \cdot E_I(t) \tag{4}$$

$$N_I(t) = P_{IJ} \cdot N_J(t) \tag{5}$$

$$E_I(t) = Q_{IJ} \cdot E_J(t). \tag{6}$$

In the case of electric field components, difference fields were not determined by Albouy & Fabriol (1981), although by analogy with the magnetic difference fields, such fields would define the anomalous electric field between sites I and J. All the empirical time domain transfer functions given in (1)–(6) can be said to be independent of time (T) if the time domain hodogram (with the first time variable as ordinate and the second time variable as abscissa) produces a linear resultant vector and if there is no departure from linearity over the record length ($2T$). The expressions as written in (1)–(6) assume noise-free fields.

If the DGS quantities K_I, L_{IJ} and M_{IJ} are determined, across a given region and over a given bandwidth, as entirely independent of time, then it is permissible to conclude that the space and time dependencies of the horizontal difference field are decoupled (Babour *et al.* 1976). In such circumstances the DGS quantities can be used to map the spatial geometry of any anomaly located in the region. Clearly the resolution of time-independent quantities in equations (1)–(3) is a function of the noise terms present in the data. The statement that the horizontal difference field is linear (i.e. the transfer functions are independent of time) must be viewed as a first- or second-order approximation depending on the noise terms present. The order of the approximation may vary with both position and period.

The present study concerns the ability of the time domain DGS technique to resolve phase differences at small station spacings. This might be thought a small point to address; however, the class of models used to explain the results of DGS studies involve a solution to the problem of electromagnetic induction in non-uniform, thin sheets (Vasseur & Weidelt

1977). Such models may be compared with two-dimensional models for which solutions to the same equations of electromagnetic induction have been formulated (Jones & Price 1970). The former models can be considered to be relatively complex in terms of the lateral extent of the region to be parameterized and hence the number of model parameters that need to be introduced. Given such a contrast between the two types of model that may be considered in relation to the results of a given experiment, it seems important to establish, from the data set, the order of any approximation as a function of both position and period. Using a three-site data set from the Borders region of southern Scotland, with a timing accuracy 1/10 that of the digital sampling period, difference field quantities are readily obtained.

The results of the application of the time domain DGS technique are then examined. An equivalent frequency domain analysis is then undertaken to determine the response functions as functions of period. Such an analysis defines the effects of both random and bias errors on the response functions obtained and therefore the extent to which they may be said to be independent of time (period).

Finally it is apparent from (2) and (3) that response functions such as L_{IJ} and M_{IJ} ultimately define three-site relationships such as:

$$H_I(t) = L_{IJ} \cdot H_J(t) + (1 - L_{IJ}) \cdot H_R(t)$$

$$D_I(t) = M_{IJ} \cdot D_J(t) + (1 - M_{IJ}) \cdot D_R(t).$$

These must necessarily be contrasted with the two-site, frequency domain, relationships normally considered in conventional geomagnetic sounding, e.g.:

$$H_I(f) = h_H(f) \cdot H_R(f) + h_D(f) \cdot D_R(f)$$

$$D_I(f) = d_H(f) \cdot H_R(f) + d_D(f) \cdot D_R(f).$$

It is clear that the time domain expressions do not include a possible dependence of (H_I, D_I) on both the horizontal components at the reference site. Such an omission presupposes a structurally simple earth. It seems necessary, therefore, to restate the formalism under which the conventional relationships of geomagnetic sounding are considered appropriate. In doing so, it is noted that difference fields are not required to establish viable field relationships at station separations of modest extent.

The data

The data come from three sites in the Borders region of southern Scotland (Fig. 1). The sites are designated I, J and R with R defining the reference. The higher geomagnetic latitude (~ 54°N) of the present study should not influence the difference fields over the site separations shown in Fig. 1. The main effect of latitude is in the type and level of geomagnetic activity recorded. The data are digitally sampled at 10 s, we here use the 12 hr of 60 s (averaged) data to parallel the bandwidth of the DGS studies. The fluxgate sensors employed at the three sites possess a noise level ±1 nT and which are therefore a factor of 5 less sensitive than the Mosnier variometers (Mosnier 1970) used in many of the DGS studies.

Simultaneous magnetic field data at all three sites allows us to examine equations (1)–(3). Simultaneous electric field data are available only at the two sites I and R and thus only equation (4) of (4)–(6) is examined. Many data sets could have been chosen to examine the relationships. The data set chosen consists of a quasi-linear inducing field (as deduced from the data recorded at the reference site) and which contains a clear noise level across the 12 hr record length.

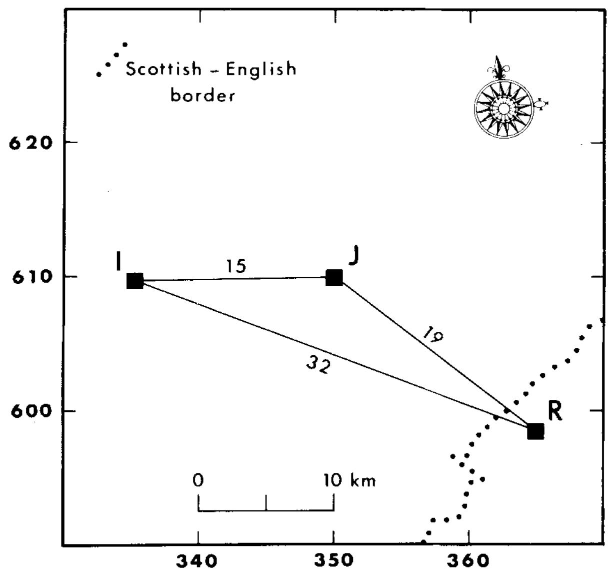


Figure 1. Location of sites I, J and R. R refers to the reference site. Sites are shown with respect to NG coordinates.

Time domain analysis

We first examine equation (1). Fig. 2(a) shows 12 hr of data at the reference site (REF) together with the difference field (DIF) between sites I and R, in the two horizontal components. The two associated horizontal field hodograms are shown below their respective data plots. The dominant event in the record is a sinusoidal oscillation of duration ~ 5000 s which is largely confined to the *H* component. Both components are subject to a noise level of ± 1 nT and this is clearly discernible in the difference fields.

It is apparent from the hodograms that phase differences exist between components but in view of the decaying spectral amplitudes within the record, the time domain hodograms do not possess adequate resolution of either the amplitude or phase relationships. To extend the time domain analysis it is necessary to inspect the various spectral components within the record using band-pass filters. This has been done in Fig. 2(b) for a set of period bands (B1–B9) which are given in Table 1. At first sight, the results displayed in Fig. 2(b) appear to validate equation (1), i.e. a linearly polarized field of given azimuth at R gives rise to a linearly polarized difference field possessing a characteristic azimuth. The extent to which equation (1) can be said to describe the field relationships is, however, discussed later.

In examining equations (2) and (3) we take the reference field as displayed in Fig. 2 and display the difference fields in *H* and *D* at the two sites I and J. The equivalent unfiltered plots are shown in Fig. 3(a) and the band-pass filtered results are shown in Fig. 3(b). The results again appear to validate at least equation (2) with the *H* component of the difference field exhibiting a real constant of proportionality over the record length which in turn gives the quasi-linear hodograms displayed in Fig. 3(b). The higher resolution of Fig. 3(b) does, however, suggest that the response function L_{IJ} is a function of time (period) and that M_{IJ}, although close to the noise level, possesses a substantial phase rotation.

Finally we examine equation (4) in Fig. 4(a, b), using the electric field components recorded at R. The difference electric field is not included in equation (4)–(6), it is, however, of interest. Fig. 4 therefore includes the difference electric field between sites I and R thus making it compatible with the magnetic field data displayed in Fig. 2. In

Table 1. Period range of the nine bands used in both extended time domain and frequency domain analyses. ND refers to the number of real degrees of freedom associated with each band.

BAND	PERIOD RANGE (s)	ND
1	7200 - 4000	32
2	5000 - 3000	32
3	4000 - 2000	64
4	3000 - 1000	64
5	2000 - 900	64
6	1500 - 800	98
7	1000 - 600	128
8	600 - 400	128
9	500 - 300	128

Fig. 4(a) we observe the apparent high degree of linearity of the electric field vector at the reference site R. The difference field vector between sites I and R displays characteristic amplitude and phase variability over all azimuths, despite the highly constrained nature of the inducing field. Both effects are seen more clearly in the band-pass filtered data of Fig. 4(b).

From the time domain results displayed in Figs (2)–(4) it might be inferred that equations (1), (2) and (4) are valid for the data set under consideration, i.e. that the transfer functions $K_{\rm I}$, $L_{\rm IJ}$ and $O_{\rm I}$ are largely real and to first order may be treated as constants and independent of time. An equivalent frequency domain analysis is now conducted to quantify fully the response functions in terms of their amplitude and phase characteristics as functions of period, to allow a comparison with the time domain results.

Frequency domain analysis

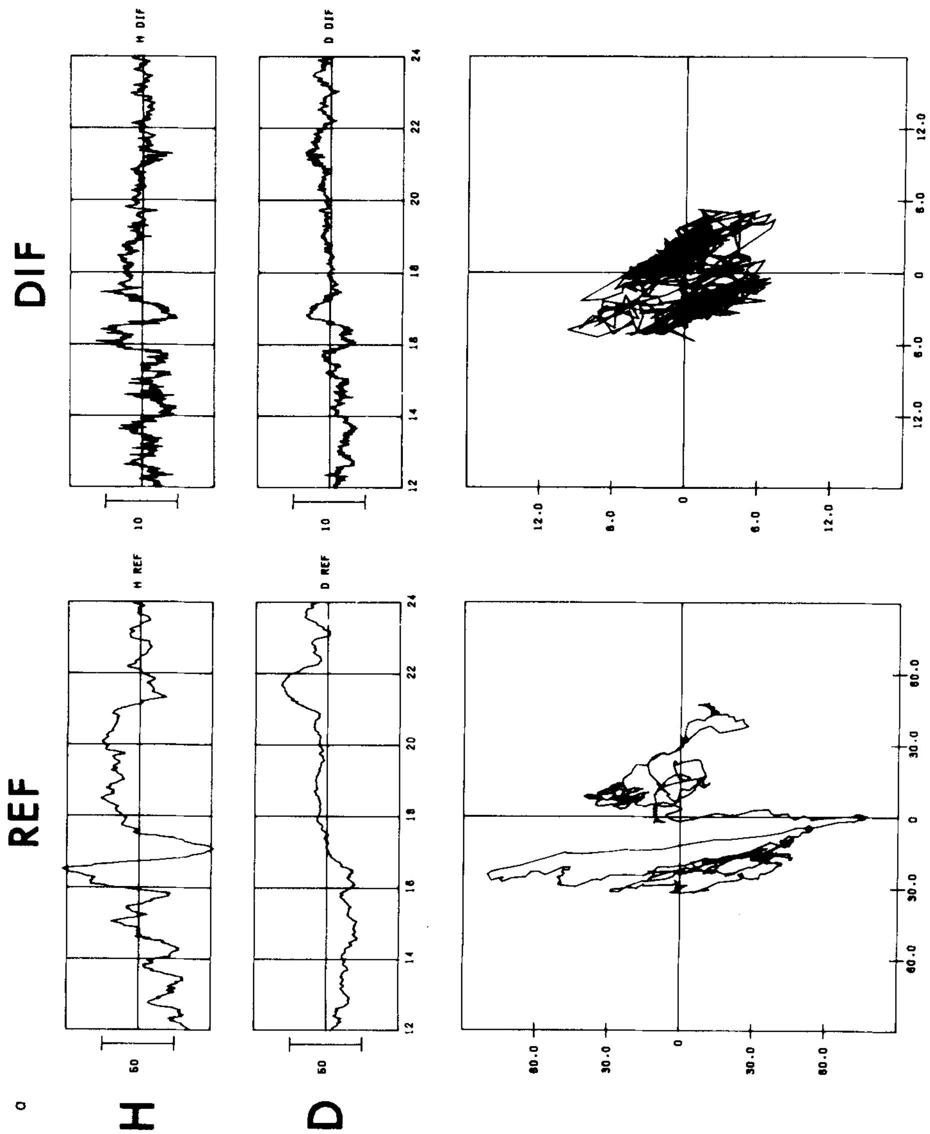
We now examine equations (1), (2) and (4) in the frequency domain using the data displayed in Figs (2)–(4). The degrees of freedom of both analyses are therefore equivalent. In the frequency domain we write:

$$H_{\rm IR}(f) = \bar{K}_{\rm I}(f) \cdot D_{\rm IR}(f) + \epsilon_{\rm K}(f) \qquad (7)$$

$$H_{\rm IR}(f) = \bar{L}_{\rm IJ}(f) \cdot H_{\rm JR}(f) + \epsilon_{\rm L}(f) \qquad (8)$$

$$N_{\rm I}(f) = \bar{O}_{\rm I}(f) \cdot E_{\rm I}(f) + \epsilon_0(f). \qquad (9)$$

These define a set of single input/single output linear relationships with all quantities complex. The frequency response functions of such linear systems may be determined by least-squares with due regard to the effects of bias and random errors (Bendat & Piersol 1971). In the case of a single input/single output response, $C(f)$, such a procedure results in lower $\bar{C}_{\rm L}(f)$ and upper $\bar{C}_{\rm U}(f)$ bounds on the true response $C(f)$ together with an estimate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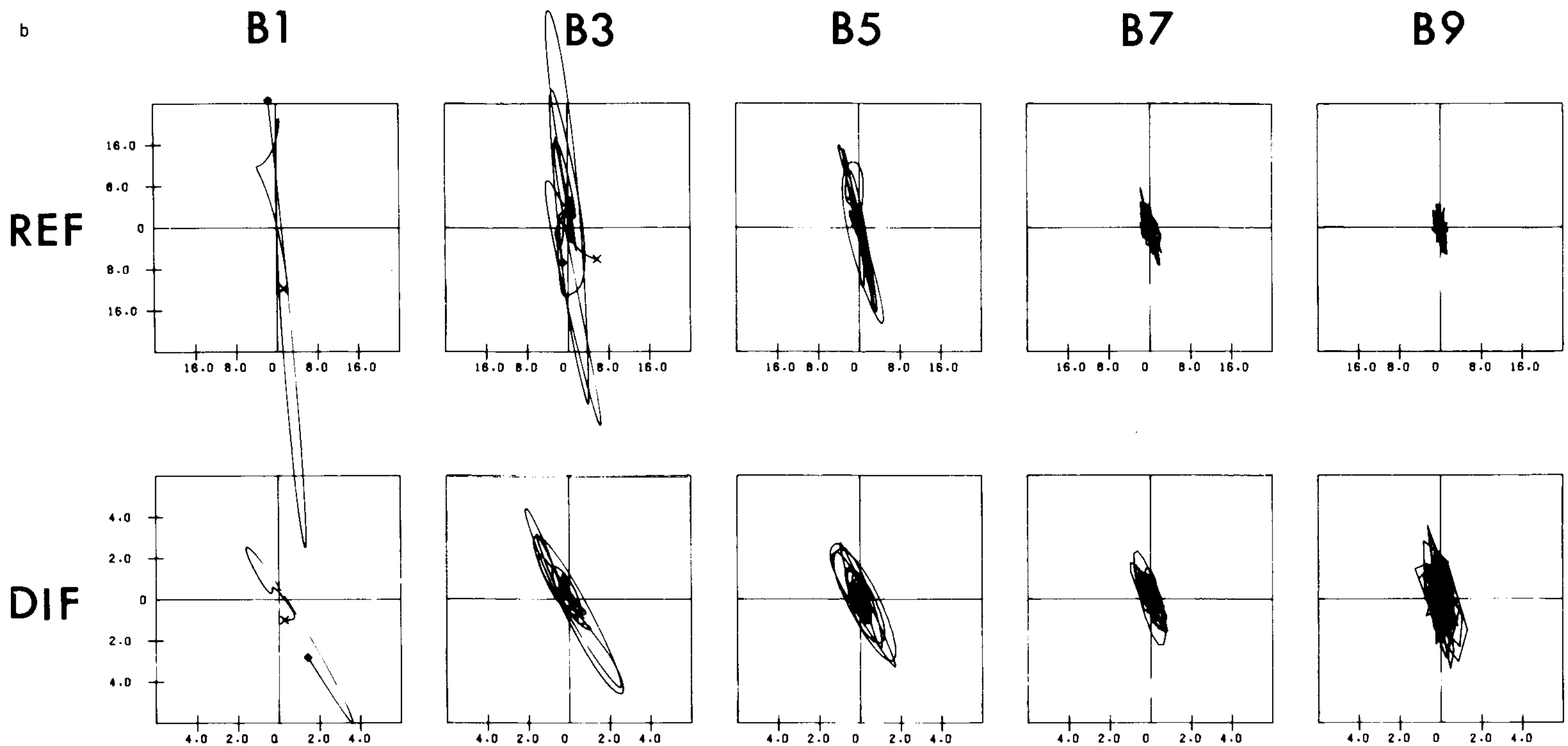
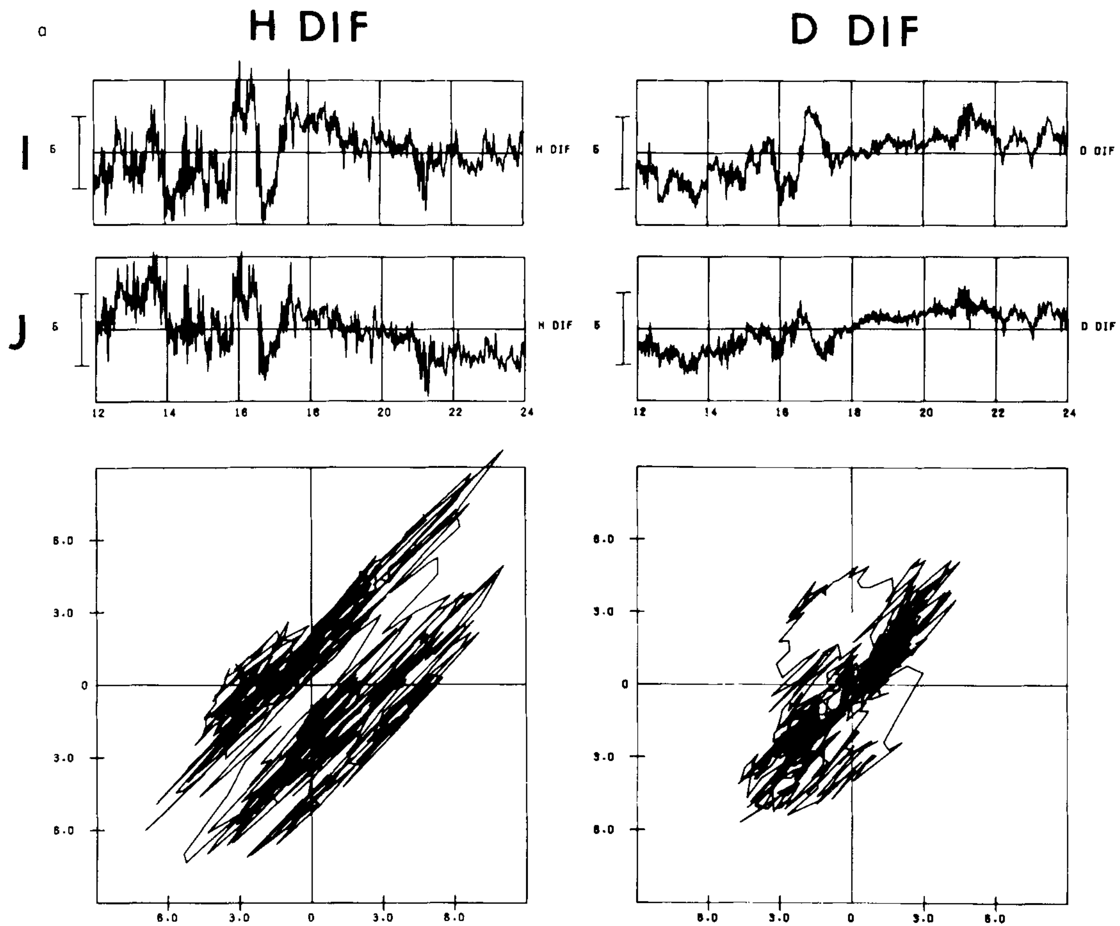


Figure 2. (a) Data relevant to equation (1). 12 hr of 60 s magnetic field data (12.00–24.00 LT) at site R (REF) and for the difference field between site I, and site R (DIF). The associated magnetic field hodograms (units of nT) are shown below their respective data plots (units of nT/1.5). (b) Band-pass filtered hodograms from magnetic field data displayed in (a) at site R (REF) and for the difference field between sites I and R (DIF). Scale bars are in nT.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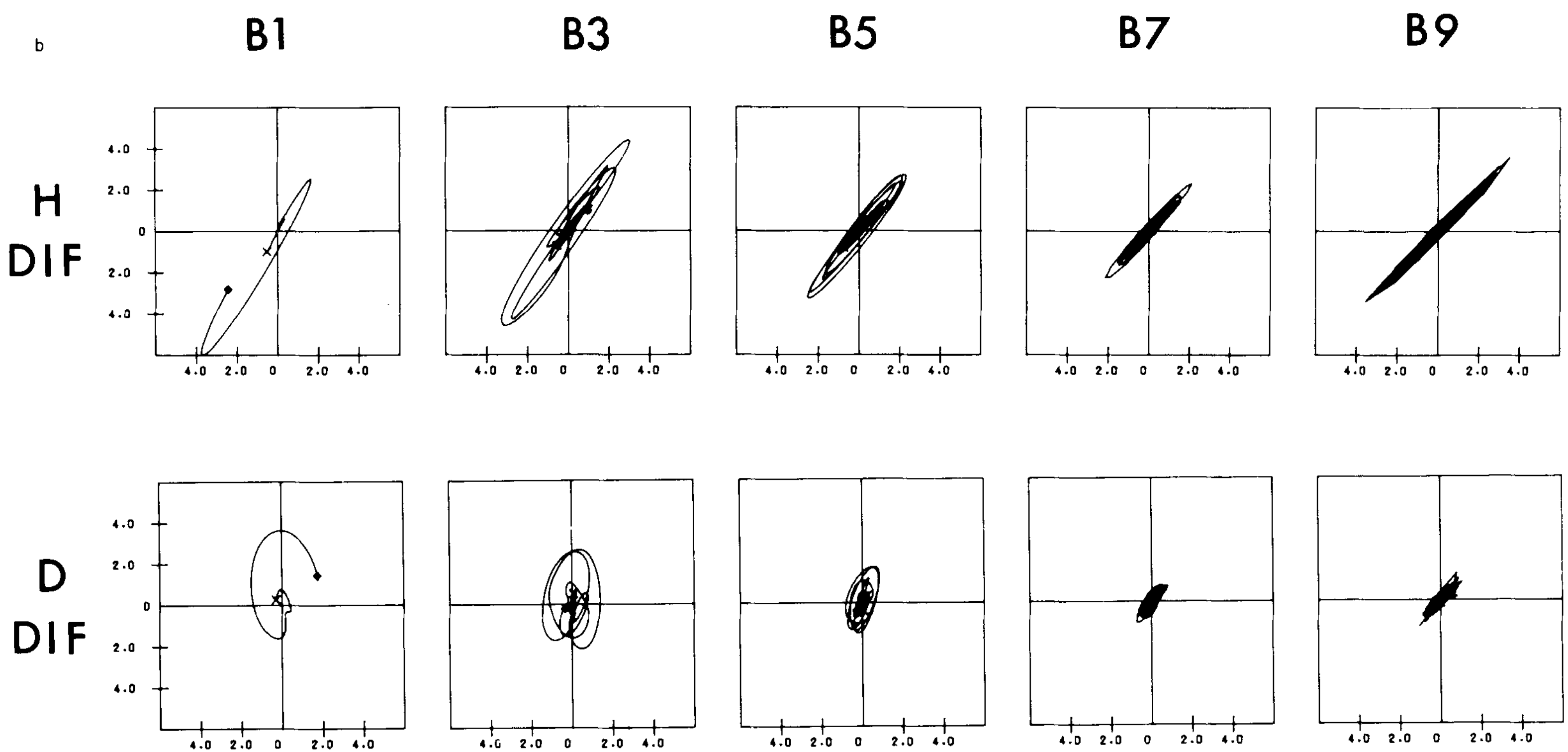
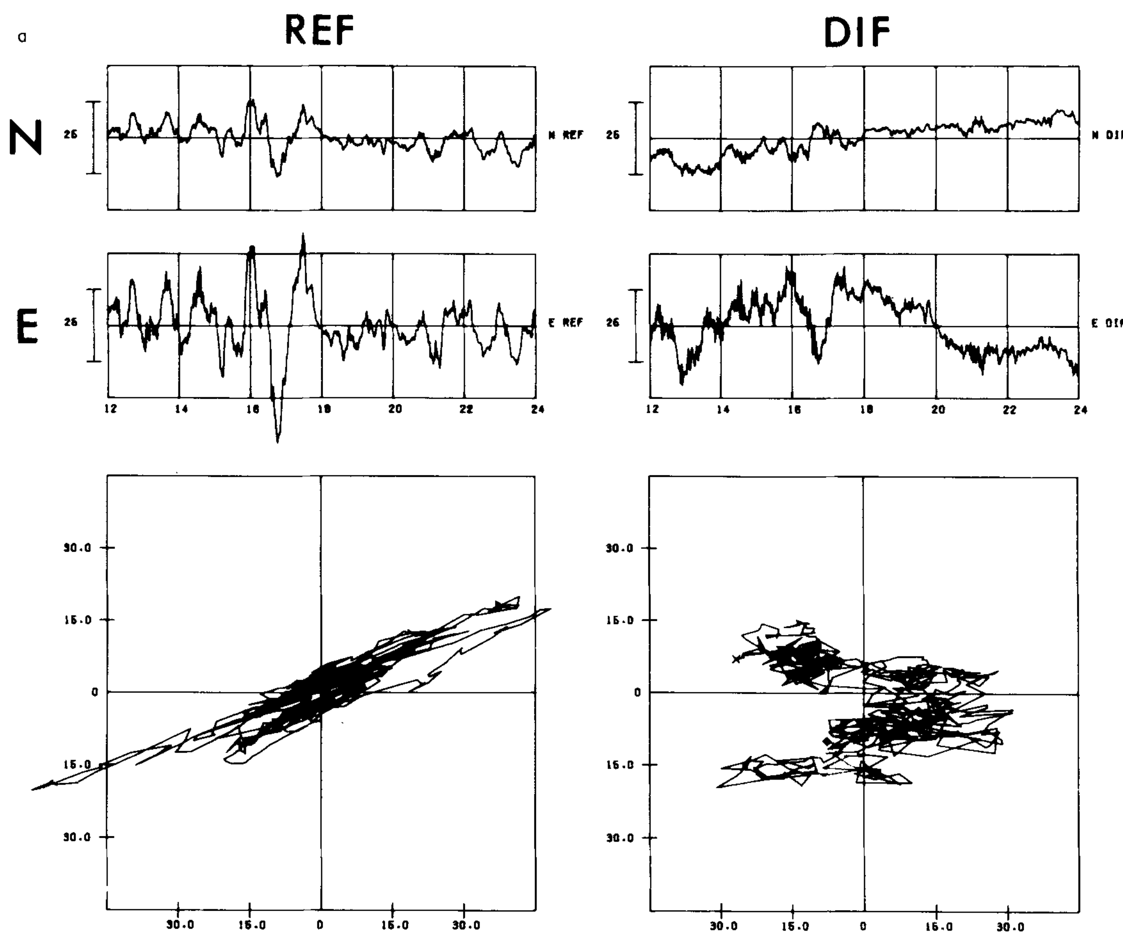


Figure 3. (a) Data relevant to equations (2) and (3). The 12hr of magnetic difference fields between sites I and R and sites J and R. The associated magnetic field hodograms (units of nT) are shown below their respective data plots (units of nT/1.5). (b) Band-pass filtered hodograms for the magnetic difference fields displayed in (a). Scale bars are in nT.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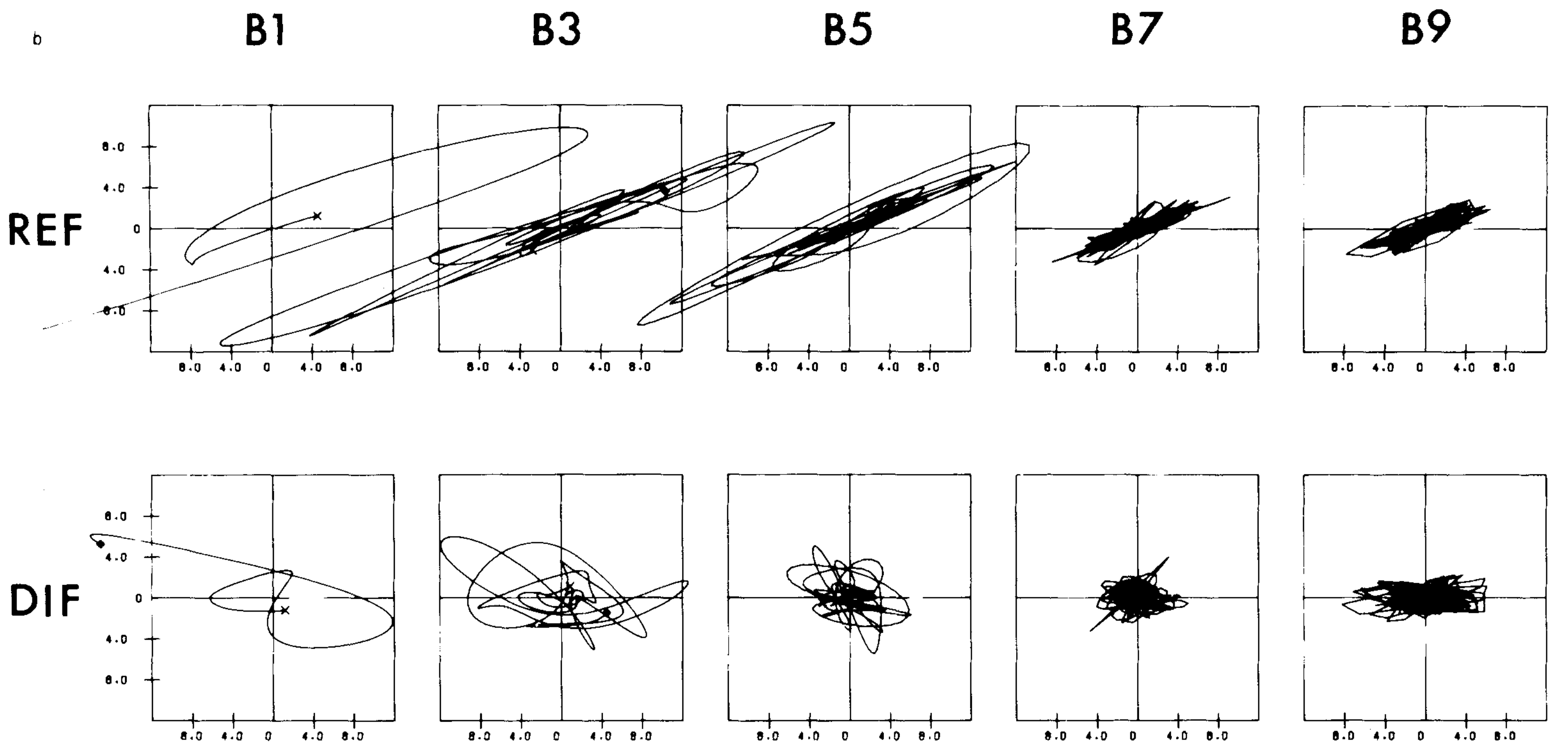

Figure 4. (a) Data relevant to equation (4). The 12 hr of 60 s electric field data at site R (REF) and for the difference electric field between site I and site R (DIF). The associated electric field hodograms (units of $mV\,km^{-1}$) are shown below their respective data plots [units of $(mV\,km^{-1})/1.5$].(b) Band-pass filtered hodograms for the electric field data shown in (a) at site R (REF) and for the difference field between site I and site R (DIF). Scale bars are in $mV\,km^{-1}$.

of the random error $\delta C(f)$ associated with $C(f)$. In the case when the ordinary coherence function $\gamma^2(f)$ between input and output becomes unity, bias errors are reduced to zero and $\bar{C}_L(f) = \bar{C}_U(f)$.

Such an analysis was carried out on the data displayed in Figs (2)–(4) using the nine period bands given in Table 1. The degrees of freedom of the bands together with the noise levels present on input and output channels ultimately define the resolution with which the response functions can be determined.

The response functions $\bar{K}_I(f)$, $\bar{L}_{IJ}(f)$ and $\bar{O}_I(f)$ are listed in Tables 2–4 respectively, as functions of period band. Their real and imaginary parts are given in terms of the limiting lower and upper bounds due to bias, together with an estimate of the random error associated with the true value of the estimate lying in the interval $[\bar{C}_L(f), \bar{C}_U(f)]$.

We are concerned here with the extent to which the response functions $\bar{K}_I(f)$, $\bar{L}_{IJ}(f)$ and $\bar{O}_I(f)$ can be said to be real and independent of period. From the results given in Tables 2, 3 and 4, it is apparent that in all three cases and at all periods, although the response functions are largely real, the imaginary part of the response is significantly determined. Furthermore, apart from the response function $\bar{K}_I(f)$ of Table 2 in which noise degrades the estimates with decreasing period, it is apparent that both real and imaginary parts of $\bar{L}_{IJ}(f)$ and $\bar{O}_I(f)$ exhibit a significant dependence on period.

Following the above time and frequency domain analysis of the DGS field relationships, we have still to address the question of the extent to which the DGS field relationships given in (1)–(3) are appropriate to the general problem of electromagnetic induction. It has already been noted that the three-site relationships of DGS are a special case (i.e. a two-dimensional earth) of a more general problem (i.e. a three-dimensional earth). We next consider the formalism within which the conventional two-site relationships of geomagnetic sounding are considered appropriate.

Table 2. The real (Re) and imaginary (Im) parts of the response function $\bar{K}_I(f)$ as a function of period band, given in Table 1. The lower and upper bounds are identified by the subscripts L and U respectively. The random error in the modulus (±1 sd) is given as δK. The ordinary coherence function is γ^2.

	$Re\{\bar{K}_L\}$	$Re\{\bar{K}_U\}$	$Im\{\bar{K}_L\}$	$Im\{\bar{K}_U\}$	$\delta\bar{K}$	γ^2
B1	1.507	1.638	-0.151	-0.165	0.0221	0.92
B2	1.617	1.683	-0.213	-0.222	0.0120	0.96
B3	1.564	1.747	-0.223	-0.249	0.0149	0.89
B4	1.500	1.849	-0.471	-0.581	0.0292	0.81
B5	1.510	1.786	-0.835	-0.987	0.0280	0.85
B6	1.316	1.921	-1.190	-1.738	0.0466	0.68
B7	1.3665	2.604	-0.918	-1.748	0.0600	0.52
B8	0.956	2.603	-0.815	-2.218	0.0665	0.37
B9	1.218	4.438	-0.540	-1.971	0.1148	0.27

Table 3. The real (Re) and imaginary (Im) parts of the response function $\bar{L}_{IJ}(f)$, and as per Table 2.

	$Re\{\bar{L}_L\}$	$Re\{\bar{L}_U\}$	$Im\{\bar{L}_L\}$	$Im\{\bar{L}_U\}$	$\delta\bar{L}$	γ^2
B1	1.474	1.569	-0.243	-0.259	0.0159	0.94
B2	1.583	1.599	-0.267	-0.270	0.0029	0.99
B3	1.521	1.555	-0.238	-0.243	0.0027	0.98
B4	1.310	1.354	-0.249	-0.258	0.0030	0.97
B5	1.182	1.204	-0.254	-0.259	0.0014	0.98
B6	1.117	1.135	-0.230	-0.234	0.0007	0.98
B7	1.063	1.087	-0.209	-0.214	0.0006	0.98
B8	0.986	1.006	-0.155	-0.158	0.0005	0.98
B9	0.995	1.005	-0.134	-0.136	0.0003	0.99

Table 4. The real (Re) and imaginary (Im) parts of the response function $\bar{O}_I(f)$, and as per Table 2.

	$Re\{\bar{O}_L\}$	$Re\{\bar{O}_U\}$	$Im\{\bar{O}_L\}$	$Im\{\bar{O}_U\}$	$\delta\bar{O}$	γ^2
B1	0.377	0.389	0.058	0.060	0.0005	0.97
B2	0.367	0.382	0.038	0.040	0.0006	0.96
B3	0.370	0.406	0.008	0.009	0.0007	0.91
B4	0.425	0.462	-0.014	-0.015	0.0008	0.92
B5	0.428	0.473	-0.010	-0.011	0.0010	0.91
B6	0.385	0.488	0.025	0.031	0.0013	0.79
B7	0.388	0.480	0.030	0.037	0.0009	0.81
B8	0.387	0.599	0.026	0.041	0.0020	0.65
B9	0.358	0.486	0.050	0.068	0.0011	0.73

Conventional geomagnetic sounding

In formulations of the general problem of electromagnetic induction, the dimensions of the external inducing field in relation to the dimensions of the internal field (a function of the scale of non-uniformity of the model earth) may appear either explicitly or implicitly. The importance of scale lengths to the general problem has been considered explicitly by

Schmucker (1973). Following Schmucker (1973) we here consider scale lengths L_1, L_2 and L_3 relating to external and internal fields and introduce L_4 which is the lateral scale length of array observations. As defined by Schmucker (1973), L_1 is the scale length of non-uniformity of the external source field (typically $L_1 = 1/k$, where k is the wavenumber). L_2 is the scale length of lateral non-uniformity of Earth structure (typically the distance between the point of observation and the nearest vertical boundary). L_3 is the scale length that determines the depth and width of the Earth that contributes to the inductive response (typically for $k \rightarrow 0$, L_3 would define the mean depth of induced currents in a stratified half-space).

In regions distant from the auroral and equatorial electrojects ($k < 1/5000\,\mathrm{km}^{-1}$) and for array observations extending to periods $< 4\,\mathrm{hr}$, we have $L_1 \gg L_2, L_3$, i.e. induction by a quasi-uniform external field in a non-uniform earth. The assumption of quasi-uniform external field ($k \rightarrow 0$, but remains finite) permits the concept of linear transfer functions between various field components as functions of frequency at one or more observation points within the array of dimension L_4.

Transfer function analysis is a statistical frequency domain procedure used to establish such linear field relationships across the array of observations. The procedure is a least-squares minimization of uncorrelated residuals between two or more sets of field components in the frequency domain. Formally we write:

$$A_{\mathrm{I}} = K_{\mathrm{IJ}} N_{\mathrm{J}} + \epsilon_{\mathrm{I}} \tag{10}$$

where all quantities are functions of frequency and ϵ_{I} is an error term which is minimized in the determination of the transfer functions K_{IJ} (Schmucker 1970). The quantities $A_{\mathrm{I}} = (H_A, D_A, Z_A)$ and $N_{\mathrm{J}} = (H_N, D_N, Z_N)$ refer to the anomalous and normal parts of the variation fields which have to be determined from the observational data.

The normal field can only be defined if $L_1, L_2 \gg L_3$, i.e. induction by a quasi-uniform external field in a stratified half-space. To obtain the normal field, the spatial gradients of the variation field across the array must be defined (Schmucker 1970, 1973), i.e. we require $L_4 \doteq L_1$. When $L_4 \doteq L_1$ and L_1, $L_2 \gg L_3$, a class of response functions relating to vertical structure is required and for this case a formal separation of the field components into internal and external parts may also be attempted (Porath, Oldenburgh & Gough 1970).

For the more practical case of $L_1 \gg L_2, L_3, L_4$, the normal field is undefined. It does, however, permit us to obtain linear transfer functions between field components of the type defined by (10). If we assume a uniform external field then $Z_N = 0$. If we assume a quasi-uniform external field with $k \rightarrow 0$ but remaining finite, we must further assume that k varies in a statistically random manner over the available data set (e.g. Beamish 1979). We formally set $N = (H_N, D_N, 0)$.

Since the normal horizontal field is undefined for $L_1 \gg L_4$, one or more reference (*cf.* normal) sites is used to establish the field relationships. It is then possible to relate the field quantities at a site (I) to the two horizontal components at the reference site (R). Two sets of equivalent expressions may then be obtained from (10):

$$\Delta H = H_{\mathrm{I}} - H_{\mathrm{R}} = h_{\mathrm{H}} \cdot H_{\mathrm{R}} + h_D \cdot D_{\mathrm{R}} + \epsilon_H \tag{11}$$

$$H_{\mathrm{I}} = h'_H \cdot H_{\mathrm{R}} + h'_D \cdot D_{\mathrm{R}} + \epsilon'_H \tag{12}$$

$$\Delta D = D_{\mathrm{I}} - D_R = d_H \cdot H_{\mathrm{R}} + d_D \cdot D_{\mathrm{R}} + \epsilon_D \tag{13}$$

$$D_{\mathrm{I}} = d'_H \cdot H_{\mathrm{R}} + d'_D \cdot D_{\mathrm{R}} + \epsilon'_D \tag{14}$$

where all quantities are complex and functions of frequency and where $(\Delta H, \Delta D)$ denote difference field quantities. Under the scale inequality $L_1 \gg L_4$, it is possible to approximate the anomalous horizontal field in (10) by subtracting the appropriate reference field quantity as in (11) and (13). This subtraction forms the basis of the DGS relationships defined by equations (2) and (3) in the time domain. Such a subtraction, performed in either the time or frequency domains, is not strictly required since it is apparent from (11)–(14) that:

$$h_H = h_H + (1, 0)$$

$$h_D = h_D$$

$$d_H = d_H$$

$$d_D = d_D + (1, 0)$$

(Beamish 1977), i.e. (h'_H, h_H) and (d'_D, d_D) differ by only the real constant of unity. We note therefore that for the case $L_1 \gg L_2, L_3, L_4$, i.e. uniform or quasi-uniform induction in a non-uniform earth, that difference field quantities are not required to establish the appropriate horizontal field relationships of geomagnetic sounding.

Conclusions

Two analyses, the first in the time domain, the second in the frequency domain, have been applied to a 12 hr data set at three closely spaced sites to examine the empirical relationships of differential geomagnetic sounding experiments. The extended time domain analysis may be taken to indicate that three of the relationships are approximately valid for the data set used. The relationships provide a measure of the anomalous field components over small distances. From the results obtained in the time domain, it might be deduced that the internal currents responsible for such fields flow locally in a purely resistive mode. The application of the frequency domain analysis to the same data set reveals, however, that such a conclusion would be erroneous. The response functions are seen to exhibit a significant phase rotation and a significant dependence on period. The time domain analysis, particularly when applied to noisy data, clearly has limits with regard to its ability to resolve such features. It is concluded that the frequency domain analysis, using standard spectral techniques, affords the greater and more meaningful resolution.

The second topic addressed in this study is the apparent lack of equivalence between the empirical relationships of DGS experiments and the formal relationships of conventional geomagnetic sounding. The question of time or frequency domain are irrelevant in this context. The formalism of conventional geomagnetic sounding has been restated and it has been noted that difference field quantities provide no additional information with regard to horizontal field relationships from array observations of modest lateral extent.

Acknowledgment

This study is published with the approval of the Director, Institute of Geological Sciences (NERC).

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