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Large-Scale Electric Field Measurements on the Earth's Surface: A Review

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There exist only a few reported measurements of quasi-stationary (near dc) electric potentials over very large spatial scales (hundreds of kilometers or more) on the Earth's surface. Such measurements have typically been made using unpowered submarine telecommunications cables. The measurements pose unique experimental challenges and require careful procedures to avoid data contamination by electrode contact potentials and local ground currents. In addition, there are possible interpretational problems from pervasive, poorly understood, low-frequency electric fields induced by ocean water motion through the Earth's stationary magnetic field. Nevertheless, estimates of the magnitude of the electric field computed from large-scale potential difference measurements, made principally to date in the Pacific Ocean, can be used to place a limit on the size of the toroidal magnetic field at the core-mantle boundary under certain conditions on the Earth's electrical conductivity profile. Thus, large-scale electric potential measurements can serve as an adjunct probe of the Earth's dynamo process in addition to measurements of the poloidal magnetic field and its secular changes made at and above the surface of the Earth. A review of all of these data suggests that the toroidal and poloidal magnetic fields at the top of the core are comparable in magnitude.

INTRODUCTION

As pointed out nearly four decades ago by *Runcorn* [1954], the measurement of very low frequency telluric currents produced in the Earth's core can provide information about core dynamo processes which are independent of those derived from magnetic field observations at the Earth's surface. In particular, measurements of quasi-steady telluric currents could yield information on the magnitude of the toroidal magnetic field and its fluctuations which are not directly observable at the surface of a homogeneous Earth, as well as the magnitudes of any potentials that might be produced by thermoelectric effects at the core-mantle boundary. Considerable progress in our understanding of the low frequency electric field at the Earth's surface has been made in recent years, particularly in ocean basins, suggesting that a reexamination of electric potential data which may bear on core processes is in order.

Surface (or telluric) electric fields arise from the existence of electrical currents flowing in the Earth. As discussed in *Meloni et al.* [1983], telluric currents can be produced by several sources: (1) fluctuations of the magnetic field at the Earth's surface caused by time-varying electric current systems in the ionosphere and magnetosphere, (2) dynamo processes within the Earth's core, and (3) motional induction caused by the flow of conducting seawater across the Earth's geomagnetic field. The significance of each of these sources depends on both frequency and the spatial scale of the source as well as the relative size of the generating mechanisms. For example, source 1 is a purely inductive phenomenon and is expected to decrease in importance with frequency since the spectra of the external fluctuations decrease with increasing frequency over a wide range ($\sim 10^{-5} - 10^{5}$ Hz) [*Lanzerotti et al.*, 1990], while source 2 is believed to be unimportant at periods shorter than a few years due to shielding by the highly conductive lower mantle [e.g., *Le Mouel et al.*, 1981]. The complications that can arise from motional induction (source 3) have become more recognized in recent years as sources of possible systematic errors in low-frequency potential measurements.

Independent of considerations of contamination by motional induction, the magnitude of the quasi-steady potential of core origin is believed to be quite small (see next section). For this reason, the few experimental investigations reported in this area of research have used long (planetary-scale) conducting communications cables as the leads for the potential measurements to increase the size

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of the signal relative to the many noise sources. For reasons wholly dependent upon the communications technology of today (which has provided the cables that have been used as the leads in the investigations), virtually all of these measurements have been made with cables that stretch across ocean basins. In addition to interpretational complexity, such configurations introduce unique experimental problems compared to their counterparts on land, as noted briefly in *Meloni et al.* [1983]. Moreover, the opportunities to make electric potential measurements over basin-scale distances appear to be increasing as older analog telecommunications cables are being replaced by their fiber optic counterparts.

Thus, it is timely to reexamine the experimental procedures for utilizing decommissioned telecommunications cables as well as their interpretation. This paper presents a short review of the present status of telluric potential measurements using planetary-scale, unpowered telecommunications cables with the emphasis on the very low frequency limit. The discussion explicitly does not include higher frequency observations which have been applied to studies of ionospheric and magnetospheric processes [e.g., *Medford et al.*, 1982, 1989; *Lanzerotti et al.*, 1992a] and magnetotelluric investigations of deep earth conductivity structure [e.g., *Richards*, 1980; *Egbert and Booker*, 1992; *Egbert et al.*, 1992], nor does it consider issues of reliability of telecommunications on long cable systems [e.g., *Axe*, 1968; *Anderson et al.*, 1974; *Lanzerotti and Medford*, 1992; *Lanzerotti et al.*, 1993]. The history of many of these topics is discussed in *Lanzerotti and Gregori* [1986].

OBSERVATIONS

Measurements of the time-average or dc potential have been made on the cable paths shown in Figure 1. All but one of these observations are from the Pacific Ocean basin and typically cover distances of 1000 km or more. While most of the data sets consist of single estimates of the dc potential difference, the measurement from Point Arena, California (hereafter, simply PA), to Hanauma Bay, Oahu, Hawaii (hereafter HB) was made independently on two parallel cables (the HAW-1 cable system) spaced approximately 100 km apart on average over the distance.

The dc potential differences determined in each of these studies are listed in Table 1. With the exception of the most recent of these reports, the measured large-scale quasi-steady electric fields are typically less than 0.1 mV/km. As with any time series, the ability to differentiate a true dc potential from low-frequency components is limited by the length of the record; according to the Rayleigh resolution criterion it is usually not possible to discriminate the dc value from components with frequencies lower than the inverse record length, depending on the relative sizes of the dc and low frequency components [e.g., *Munk and Hasselman*, 1964].

A description of the measurement procedures on the California to Hawaii cables has been given by *Lanzerotti et al.* [1992*b*]. The total impedance of each cable is about 8000Ω. This corresponds to approximately 5200Ω for the resistance of the cable center conductor, with the remainder coming from the total resistance of the cold repeater filaments (57 for the north cable and 58 for the south cable) in series. The center conductors of each cable are grounded

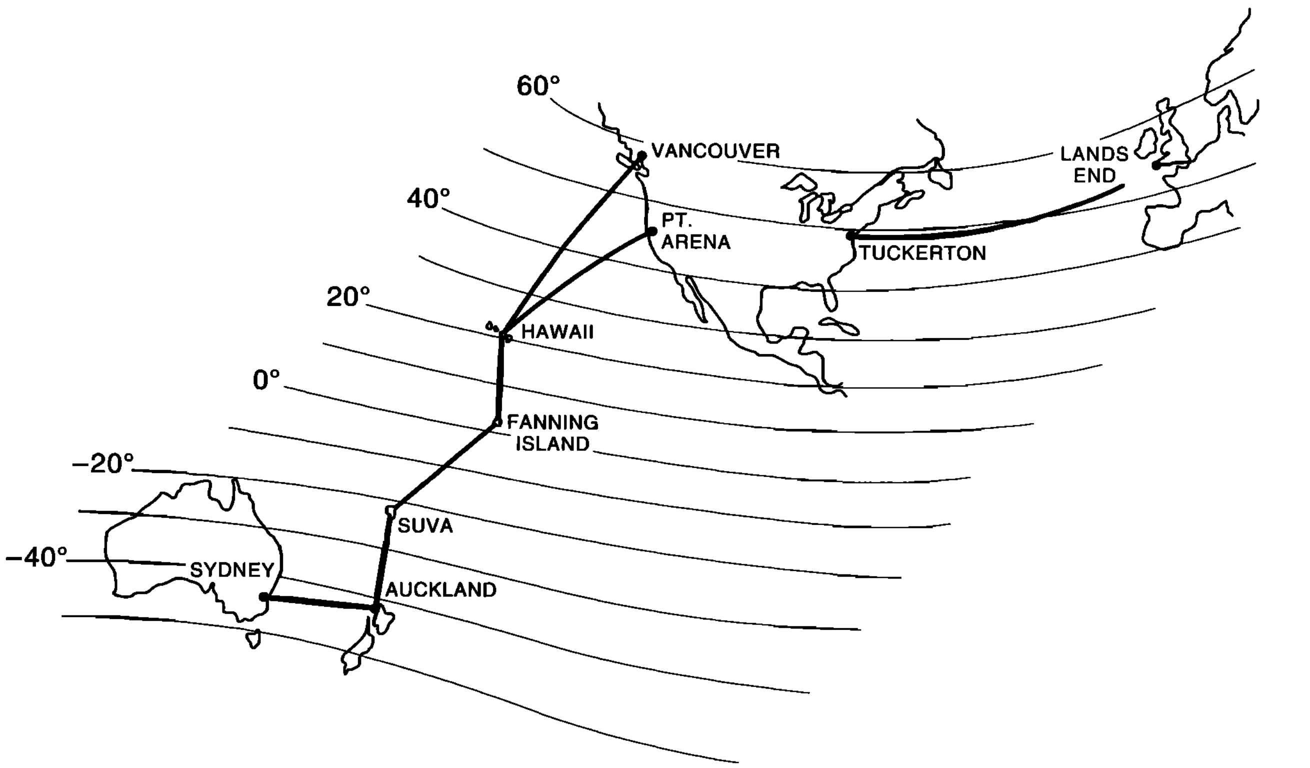

Fig. 1. Locations in the Atlantic and Pacific oceans where dc potential measurements have been made using long cables (see Table 1).

TABLE 1. Long Distance DC Earth Potential Measurements

Cable Parameters		Time Interval,	Electric Field,	
Shore Terminals	Length, km	Days	mV/km	References
Suva to Auckland	~2250	4	<0.1	*Runcorn* [1964]
Sydney to Auckland	~2600	4	<0.1	*Runcorn* [1964]
Suva to Bamfield	~9660	85	<0.03	*Duffus and Fowler* [1974]
Tuckerton to Lands End	4471	19 (all data)	-0.076 ± 0.067	*Lanzerotti et al.* [1985]
		5 (quiet data)	-0.028 ± 0.063	
Point Arena to Hanauma Bay	4050	368 (all data)	0.205 ± 0.101	*Lanzerotti et al.* [1992*b*]
		69 ($Ap \leq 5$)	0.183 ± 0.056	

to the Earth in Hanauma Bay, Hawaii, using the telecommunications sea-bed ground. At the California terminus, the ground is a specially installed telecommunications standard silicon-iron ground rod. The center conductors of the cables are tightly insulated from seawater contact. The outer shield of each cable as well as the repeater housings are in seawater contact, but this is not of relevance for the measurements or for the use of the cables in a telecommunications system. The voltage differences between the center conductors of the cables and the Point Arena ground are measured with a high impedance ($\sim 1\,\mathrm{M}\Omega$) voltmeter after first resistively dividing the signals by a factor of $\sim 10^3$. In effect, a cable serves as a very long lead of a high impedance voltmeter. The complications, as discussed herein, arise because seawater flows across the lead, and ionospheric and magnetospheric currents cause induced telluric potentials to be produced across the lead.

In addition to the long cable observations, there are several reports of year-long (or more) measurements of telluric electric fields using the autonomous short span sensors described in *Filloux* [1987]. These instruments utilize electrode reversal or chopping techniques to explicitly remove electrode and most electronic drift, and are fully usable in the dc limit. However, for reasons discussed in more detail below, the dc potential typically reflects the average water velocity over the available record rather than any nonmotional sources and is not considered further in this paper.

Larsen and Sanford [1985] and *Larsen* [1992] report on multiple (up to 14) year records of the potential difference from a short abandoned cable spanning the Florida Straits. These data are dominated by the mean and fluctuating transport of the Gulf Stream which generates potentials in excess of one volt across about 100 km, and a search of them for core-induced fields would be fruitless. Of the available terrestrial electric field records, the longest and most carefully examined appears to be a 12-year series collected largely in the 1930s near the Tucson magnetic observatory [*Rooney*, 1949]. These data have been reanalyzed recently by *Egbert et al.* [1992], and appear to be dominated by noise sources of indeterminate origin at periods over 10 days. Thus, the cable measurements reported in Table 1 appear to be the most relevant to investigations of core processes, and are reviewed more critically.

LIMITATIONS ON THE MEASUREMENTS

The experimental difficulties involved in establishing an absolute potential difference of the order of a volt over a large distance are formidable. Some of the problems are similar to those encountered in measurements of electric fields over short (~100 m) distances in ordinary magnetotelluric studies on the Earth's surface, especially those associated with time-variable electrode offset voltages. Further, all of the reported measurements to date have used decommissioned ocean cables; there do not appear to be land-based cables of sufficient length that long duration measurements can provide the potential drop and electrode stability required for measuring very small electric fields (although this point requires further investigation).

As discussed in *Lanzerotti et al.* [1992*b*], any large-scale, mean Earth potential from the seafloor V_{dc} can be expressed as

$$V_{dc} = V_e + V_O + V_C \tag{1}$$

where V_e is the potential from possible electrochemical effects at the ground electrodes, V_O is a potential from very low frequency or mean ocean flows, and V_C corresponds to possible quasi-steady Earth potentials, such as those that might arise from the leakage of poloidal electrical currents from the core through the mantle to the Earth's surface. These will be discussed in turn.

Electrode Contact Potentials

As in all types of telluric studies, stable contact potentials of the electrodes are critical for establishing the low frequency reliability of the results. In land-based studies, the electrochemical environment around the electrodes can change rather rapidly with time. For example, rainfall can alter the local ground conductivity and chemistry, or the electrodes can dry out due to solar heating, resulting in data that are typically dominated by electrode drift at periods longer than a few hours when the usual measurement span (~100 m) is used. This has led to extraordinary approaches, such as the use of long grounded communications cables so that the natural signal will be large enough to swamp electrode drift [e.g., *Rooney*, 1949] or placing the telluric array in the relatively stable environment at the bottom of a lake [*Schultz et al.*, 1987]. For ocean cable studies, the electrode environment might be expected to be more stable. Nevertheless, the chemistry of the electrode environments can change with time for a variety of reasons, including possible differences in the chemistry of the ocean between the cable landing sites. In an ideal situation, the net effects of two essentially identical electrodes should be null.

The first three entries in Table 1 used cables with electrodes that probably had been in place, and thus locally stabilized, for some long interval before the measurements reported were made, although this is difficult to assess after the fact. Only the last two entries in Table 1 discuss the specific electrode configurations involved in the measurements in sufficient detail to allow electrode effects to be assessed. In the case of the Atlantic cable, the differences in electrochemical potentials of the material used for the ocean and shore electrodes had to be invoked in order to arrive at the results presented. In the case of the last entry (the measurement from PA to HB), the electrode at the California side was new, in contrast to that at the HB end, which used an electrode, that, although made of the same type of material, had been in place for nearly three decades. It might be expected that a new electrode would require some interval, depending upon the ground/ocean conditions, to come to a stable condition.

At most ocean cable landing stations there are active communications systems with their own associated power and ground systems. An additional problem occurs when the ground electrodes are simultaneously used to terminate active communications cables, as is the case for the fourth entry (whether on not this was the case was not discussed for the first three entries in Table 1). If a shared ground system is used, the measured potential must be corrected for the currents flowing from the highly regulated constant current power supplies of the active system. For example, the "correction" required for the fourth entry was of the order of the measured effect. Even if separate ground electrodes are available, the measurements must be checked to determine if there are any effects from stray ground currents from any nearby cable power systems. The relatively isolated (from dense human populations) landing sites of many cables may render the effects of possible low frequency fluctuations in power grids negligible, although this must also be determined more precisely.

Although not specified precisely in the case of the first three entries in Table 1, it is likely that these measurements used electrodes provided originally by the company that installed the communications system. Thus, none of these electrodes were of the silver-silver chloride (Ag/AgCl) nonpolarizing type in common use for low frequency ocean bottom studies over short spans [e.g., *Filloux*, 1987]. Such electrodes are believed to provide the smallest contact potentials and best long-term stability for ocean bottom work. It is currently planned to make measurements on the abandoned HAW-2 cable which stretches from San Luis Obispo, California, to Makaha, Oahu, Hawaii using Ag-AgCl electrodes as an experimental test of the importance of contact potential variations.

Motional Induction

Since the time of *Faraday* [1832], who used a thin wire stretched between two copper plates across the River Thames in a failed measurement attempt, the motion of ocean water through the Earth's magnetic field has been recognized to induce telluric currents. Tidal studies using cables have long been carried out [e.g., *Stommel*, 1954; *Prandle and Harrison*, 1975; *Richards*, 1977; *Thomson et al.*, 1986]. The theory of motional induction has been examined by many individuals [e.g., *Stommel*, 1949; *Longuet-Higgins et al.*, 1954; *Sanford*, 1971; *Chave and Luther*, 1990] in the low frequency limit where the electric field at a point is proportional to the vertically integrated, seawater conductivity-weighted water velocity. For a submarine cable, additional horizontal averaging obtains, as this quantity is integrated along the cable. For a flat-bottomed ocean without boundaries, the cable electric field would very nearly yield the volume transport across the oceanic section spanned by the cable. The interpretation becomes more complex in the presence of real seafloor topography and other complications, as discussed in detail by *Larsen* [1992].

The importance of motional induction relative to external sources for low frequency electric field measurements made on the seafloor is vividly illustrated by Figure 2, which compares the spectrum of a 10-month-long record from the North Pacific collected with a short span (~6 m) electric field instrument described by *Filloux* [1987] to that predicted from the magnetic field. Motional magnetic fields have not been detected except at tidal periods [e.g., *Chave et al.*, 1989; *Luther et al.*, 1991] and hence the magnetic field serves as a measure of externally induced electric currents. *Luther et al.* [1991] converted the spectrum of the magnetic field to that of the externally induced electric field using a transfer function that depended on the conductivity structure beneath the seafloor. The motional component clearly dominates the electric field at periods longer than a few days in Figure 2. Whether such an effect continues to lower frequencies than are resolvable with the ten month record available to those investigators is not certain. However, based on theoretical arguments and the known variability of the ocean's velocity field, the effect is likely to continue to lower frequencies. The size of the motional fields will depend heavily on location because of the known variability of the kinetic energy level in the

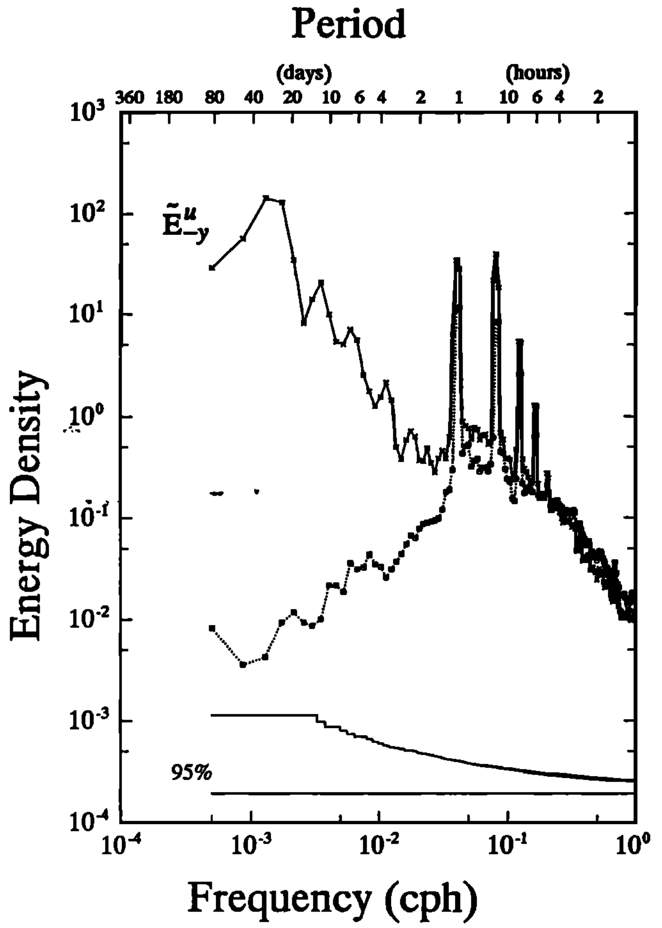

Fig. 2. Energy density as a function of frequency in ocean bottom electric field measurements (crosses) and electric field as derived, via a transfer function technique, from measured magnetic fields on the seafloor (square points). The confidence limits are given for the transfer function analysis [from *Luther et al.*, 1991].

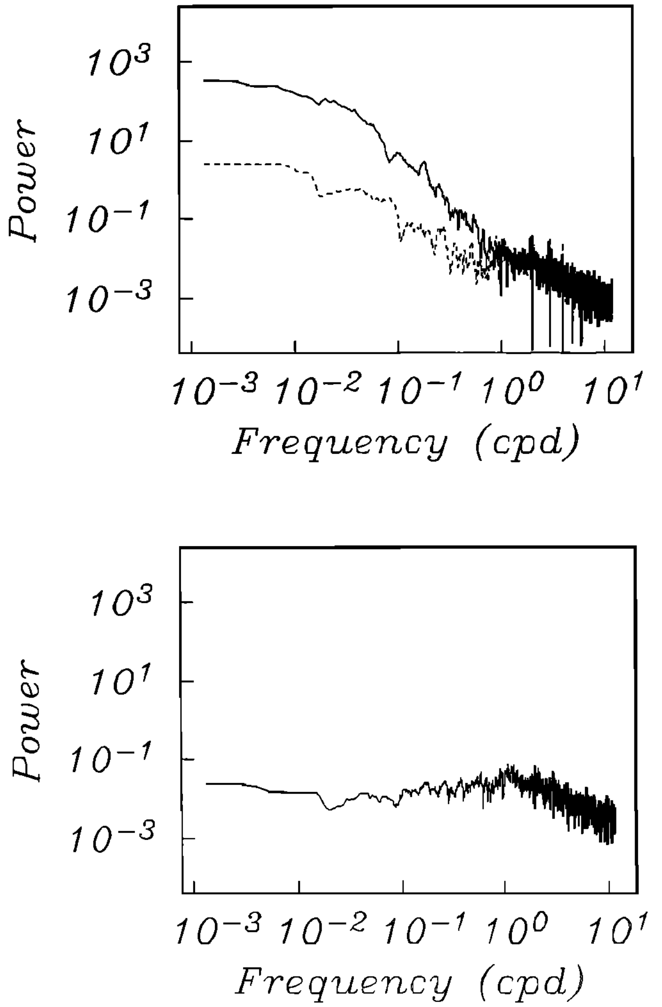

Fig. 3. Power spectra (in $mV^2 km^{-2}$/cpd) of hourly means of the electric field from HAW-1 for the time interval April 1990 to April 1991 (lower panel) and for two year-long time series of the north electric field component collected with point sensors on the ocean bottom (top panel). In the upper panel, the solid line is for data taken under the Gulf Stream while the dashed line is for data acquired in a weak eddy variability region in the northern Pacific [from *Chave et al.*, 1992].

ocean, with the largest values observed near western boundary currents such as the Gulf Stream. Figure 2 was estimated from a very quiescent part of the ocean where the kinetic energy level was about 100 times smaller than would be observed under the Gulf Stream.

The situation is complicated when spatially extended sensors like submarine cables are used because those field components whose spatial scales are of the order of the cable length or smaller will tend to be averaged away. This is especially important for motional fields because their scale is that of the oceanic velocity field, typically 1000 km or less. By contrast, the low-frequency field induced by external sources depends upon the location of the sensing cable with respect to the source: the equatorial ring current (typically located several Earth radii above the Earth's surface, the equatorial electrojet, auroral electrojets, etc. While some external sources can be considered of planetary scale, there are significant smaller scale sources whose effects will also tend to be reduced by spatial averaging. Because of the smoothing effect produced by diffusion through the highly conductive lower mantle, electric fields from the core dynamo are unlikely to contain small spatial scale components.

This qualitative picture is supported by the recent study of *Chave et al.* [1992] using a 1-year-long record from the HAW-1 cable which runs from PA to HB. Figure 3 compares the power spectrum of the electric field estimated from the cable with two short-span electric field records of comparable duration. In contrast to the latter, which typically have enhanced power at frequencies below 1 cpd or so, the cable spectrum is nearly independent of frequency to the lowest frequencies that can be resolved. That this is caused by spatial averaging of the motional fields is supported by coherence analyses with both the magnetic field at standard observatories and with the wind stress curl which drives most of the oceanic fluctuations. *Chave et al.* [1992] concluded that motional induction remained dominant at periods over about 2 weeks, although the motional field clearly remains weakened by spatial averaging, as seen in Figure 3. This strongly suggests that large-scale electric potential measurements offer the best chance of separating very low frequency core dynamo fields from those produced by other sources.

For the present purposes it is sufficient to note that any small dc potential estimated from the long-term average of an ocean cable measurement could conceivably be attributable to the net transport of water over the cable section. *Winch and Runcorn* [1991] have raised such an issue with respect to cables in the southern Pacific. Such transports and the corresponding electric potentials could be quite large when the cable crosses only a portion of a gyre; for example, a cable which crosses the Gulf Stream might produce a mean potential difference of order 5 V at midlatitudes. This potential would be substantially reduced if the cable crossed the entire Atlantic basin to include the return flow. Large motional contributions would also be expected to be observed on cables that cross the North Pacific western boundary current, such as the Guam to Japan and Guam to Philippines segments of the Trans-Pacific Cable 1 (TPC-1). The PA-HB (HAW-1) cable crosses a weak eastern boundary current whose importance is more difficult to assess. It is likely that a cable lying in a midgyre region, such as the TPC-1 segments connecting Wake, Midway, and Hawaii, would offer the best opportunities for studies directed toward processes in the Earth's core. Plans are presently being made to instrument these cables.

It should also be emphasized that very low frequency (e.g., interannual to climatic time scale) fluctuations of the ocean might produce slowly varying electric fields which cannot be discriminated from the true dc value given time series data of the length that might realistically be obtained. Present understanding of interannual fluctuations of the oceanic gyres is not adequate to even begin to estimate the size of this effect. As a mitigating factor, and as discussed earlier, it should be noted that *Chave et al.* [1992] have clearly shown that a cable measurement provides a much better possibility for determining a dc term buried in the stochastic background electromagnetic spectrum than does a point electric field measurement because the motionally induced fields are substantially reduced (see Figure 3). At the present time, it is probably most prudent to estimate the mean electric potential using long, variable length segments of data taken from quiescent parts of the ocean. If this quantity is stable to within the statistical uncertainty as the segment length is increased, then it is less likely that low frequency motional induction is masking the mean voltages from other sources. Conversely, if the value depends strongly on the averaging scale, then it is unlikely that a useful estimate of the mean can be obtained.

HAW-1 Observations

Some questions about the stability of the reported measurements can be addressed by further analyses of the only time series of data still being acquired, that from PA to HB. The southern of the two cables between these two locations broke approximately 200 km off the Hawaii coast in April 1991, shortly after the end of the data interval reported in *Lanzerotti et al.* [1992*b*]. The cause of the break is unknown. It is the only such break encountered on these cables in this area since they were laid in 1957.

Figures 4*a* and 4*b* show the 30-day averages and their standard deviations for the large-scale electric fields measured on the north (unbroken) and south (broken) cables, respectively, from the time measurements began in April 1990 until May 1992, more than 2 years later. Because of down times of the recording equipment for maintenance, etc., some of the intervals include one or two days less than 30 days of data. The averages were computed by first determining the 20-min medians of 2-s data points. Daily averages were then computed from the 72 median points for each day. These daily averages were then used to calculate the 30-day averages. The standard deviations shown are determined from the daily average data values alone. The linear fit to the data, weighted by the standard deviations, in Figure 4*a* for the unbroken north cable, shows a systematic decrease in electric potential with time, at a rate

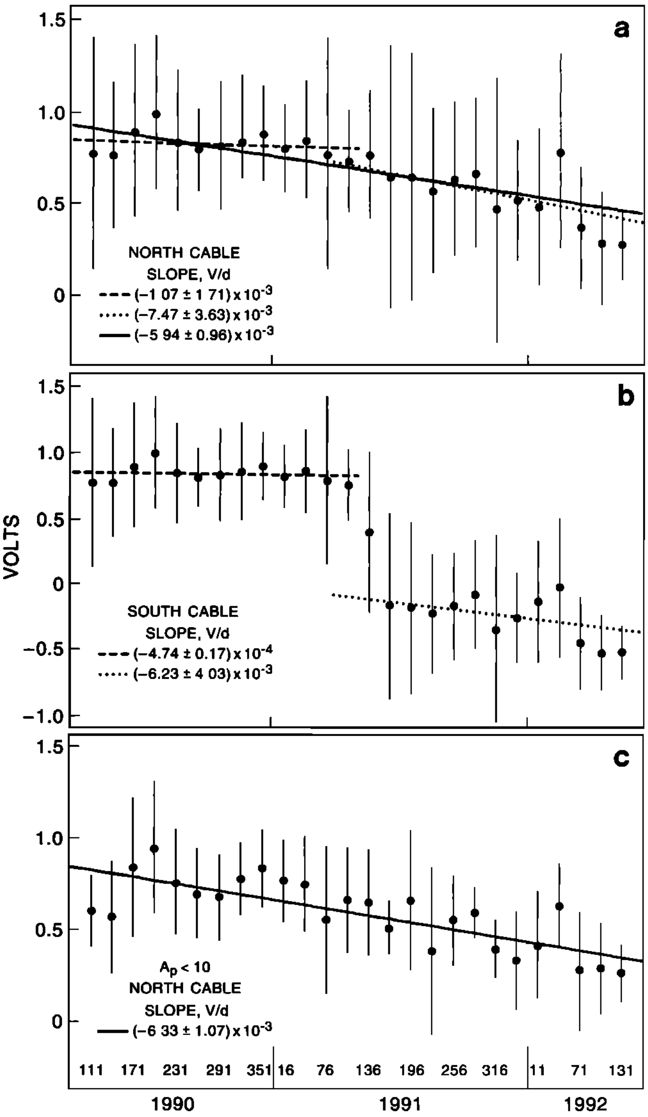

Fig. 4*a*, *b*, and *c*. Time history of 30-day average potential measurements on the north and south cables of the HAW-1 cable system. The slopes of the best fit lines (weighted by the standard deviations) through the designated data intervals are given.

of 6 mV/d. For the approximately 2 years of data shown, the average electric field is 0.070 ± 0.048 mV/km.

Comparing the slopes for the data sections in Figures 4*a* and 4*b*, it is evident that they are approximately the same for the two cables for the data segments before and after the time of the break in the south cable (distinguished by the offset in the south cable data; the offset occurs because of the change in electrode characteristics from the Hawaii ground bed before the break to the copper center conductor direct contact with the ocean water after the break). Further, inspection of the individual 30-day average points in both cables before and after the break show quite similar relative changes from average value to average value with time.

The selection of only those days in each 30-day interval with a daily geomagnetic activity index $Ap<10$ (Figure 4*c* for the unbroken north cable) shows no significant difference in the rate of change in the electric field over the 2 years between quiet and disturbed conditions (although, as shown in *Lanzerotti et al.* [1992*b*], the overall average potential value is lower in the case of geomagnetic quiet times).

The similarity of the relative changes in the 30-day averages of the data from the two cables before and after the southern cable break would argue against an electrode change at Hanauma Bay as being the cause of the measured electric field drift with time over the 2 years. The most straightforward interpretation of the drift is that the electrode contact potential at Point Arena, common to both cables, is changing with time as the electrode ages. There is no independent verification of this at present; discussions are underway on how possibly to test this experimentally.

An actual change in the potential from a geophysical source (or sources) cannot be ruled out at this time. For example, there may be secular variation in the electric potential, just as is observed at terrestrial magnetic observatories for the magnetic field. There is no a priori reason to believe that secular change in the poloidal magnetic field will be mirrored in the presumably toroidal magnetic field and its associated poloidal electric field, although this should be assessed using observatory magnetic records. This picture might be complicated by the presence of conducting pathways which electrically connect the ocean to the deep mantle, as has been observed at a subduction zone [*Wannamaker et al.*, 1989], which would couple the electromagnetic fields associated with the two modes (see next section). Finally, there is at present no way to rule out interannual fluctuations of the North Pacific gyre or the California Current as a cause for the trend shown in Figure 4. These problems are probably best addressed when substantially longer time series become available for analysis.

DISCUSSION

Independent of the temporal behavior of the most recent measurements of the large-scale quasi-dc Earth potential, some bounds can be placed on its magnitude based on the measurements which have been reported (see Table 1). It appears that the large-scale electric field of core origin must be ≤ 0.1 mV/km, a value similar to that originally deduced by *Runcorn* [1954; 1964]. In fact, the summary of measurements suggests that the field is perhaps as small as one-half of this upper limit.

Even if such small potentials are eventually determined to arise from oceanic sources, these upper limits can be used to bound the magnitude of the toroidal magnetic field at the core-mantle boundary. Since $\nabla \cdot \mathbf{H} = 0$ in the Earth's mantle, the magnetic field $\mathbf{H}$ can be expressed as the sum of two scalar functions,

$$\mathbf{H} = \nabla \times \mathbf{A} \tag{2}$$

where

$$\mathbf{A} = \mathbf{r}\Phi_E + \mathbf{r} \times \nabla\Phi_M \tag{3}$$

and

$$H_E = \nabla \times (\Phi_E \, \mathbf{r}) \tag{4}$$

$$H_M = \nabla \times (\mathbf{r} \times \nabla\Phi_M) \tag{5}$$

The terms in (4) and (5) describe, in the geomagnetic dynamo theory, the toroidal (electric) and poloidal (magnetic) modes, respectively [see reviews in *Busse*, 1983; *Roberts*, 1988]. The poloidal mode consists of magnetic field lines of force wrapped around spherical surfaces and the toroidal mode consists of magnetic field lines with radial components. The toroidal magnetic field is essentially confined to the highly conducting core. However, under some assumptions as to the conductivity of the Earth's mantle, the electric field from the electric currents that generate the toroidal magnetic field can be measurable at the Earth's surface.

The work of *Runcorn* [1954] motivated the analytical work of *Roberts and Lowes* [1961]. These authors investigated the possible magnitude of the electric field under several assumed distributions for the mantle electrical conductivity profile $\sigma(r)$, all of which decreased monotonically with increasing distance r from the Earth's core. In spherical harmonic terms, they showed that, in electromagnetic units, the tangential component $H_n(r)$ of a toroidal magnetic field of order n at the core-mantle boundary ($r=c$) could be related to the magnitude of the tangential component $E_n(r)$ of the poloidal electric field component of order n at the top of the mantle ($r=a$) by the dimensionless ratio

$$N_n = \frac{|H_n(c)|}{|E_n(a)| 4\pi c \sigma(c)} \tag{6}$$

Shown in Figure 5*a* are the toroidal magnetic fields from (6) for different values of the poloidal electric field measured at the Earth's surface for $N_n = 1$. Figures 5*b* and 5*c* present the toroidal field at $r=c$ for different factors of N_n for poloidal electric fields equal to 0.05 and 0.15 mV/km at $r=a$. If values of the lower mantle conductivity inferred from studies of the secular variation of the poloidal magnetic field are used (about 10^2 to 10^3), then the toroidal magnetic field at $r=c$ would be in the range of a few gauss, comparable to the dipole component of the poloidal magnetic field at that

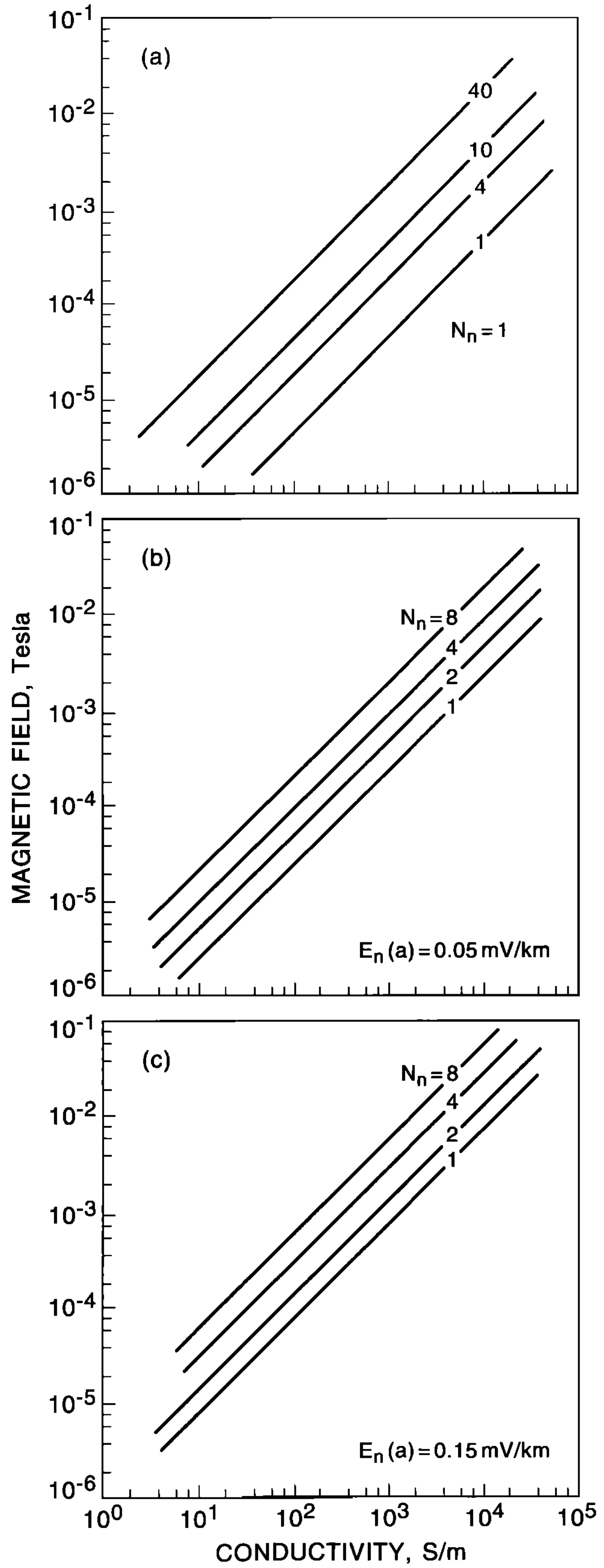

Fig. 5. Magnitude of the toroidal magnetic field at the top of the core as a function of the conductivity at the bottom of the mantle, determined from Eq. (6) as analytically derived by *Roberts and Lowes* [1961]. (*a*) For $N_n = 1$ for four values of the poloidal electric field measured at the top of the mantle in units of 10^{-2} mV/km. (*b,c*) For two values of the poloidal electric field measured at the top of the mantle for four values of N_n each.

location (i.e., as extrapolated from the Earth's surface). The toroidal field some distance inside the core would be larger [*Roberts and Lowes*, 1961].

In addition to the experimental uncertainties that exist and that only permit upper limit deductions for V_c at present, there are complicating matters that arise because of uncertainties about the conductivity structure of the Earth's mantle. A number of these were discussed in *Lanzerotti* et al.[1985], and the situation has grown more complex in the last half-dozen years. For example, the study of *Roberts and Lowes* [1961] used conductivity profiles that were analytically tractable, as essentially had to be the case at the time the work was done. Needed today are studies of somewhat more complex profiles, including adaptations of the models of *Backus* [1982], who found by a perturbation analysis that a conductivity profile with only one local minimum in the mantle will create a critical layer that will largely screen out any electric field of internal origin (except for the case where the critical layer occurs at or near the Earth's surface).

It is interesting to note that a sharp local conductivity minimum near the top of the upper mantle is a robust feature of recent syntheses of oceanic electrical data [e.g., *Chave et al.*, 1990]. This would ordinarily suggest that the ocean might be nearly electrically isolated from the deep mantle, leading to screening of internal electric fields, depending on the actual width of the critical layer. However, strong electrical coupling of the ocean to the deep mantle has been observed in the EMSLAB study of the Juan de Fuqa plate at the subduction zone off of northwestern North America [*Wannamaker et al.*, 1989], and probably exists at other subduction zones in the world oceans. There are other candidate conductive pathways between the ocean and mantle, such as at midocean ridges, continental margins, and possibly midocean hot spots, although these are purely speculative at this time. This suggests that more complex, higher dimensional models of the ocean basins are really required to address this problem with sufficient realism. Numerical simulations of electric field diffusion through more "realistic" mantle conductivity profiles are needed in order to explore more widely the range of parameter space in which to interpret (and expect to find) large-scale electric field measurements on the surface of the Earth.

Theoretical computational analyses would also allow examination of the relationship of the interpretations of mantle conductivities inferred from geomagnetic "jerks" in the geomagnetic secular variation [e.g., *Courtillot et al.*, 1978; *Ducruix et al.*, 1980; *Malin and Hodder*, 1982; *Nevanlinna*, 1984; review by *Courtillot and Le Mouel*, 1984*a*, *b*] to the $\sigma(c)$ used here. It should be noted that *Alldredge* [1984] has called into question the interpretation of the measured geomagnetic "jerks" as purely an internal Earth process (in contrast to the possible influences of external processes such as solar cycle-dependent geomagnetic activity). *McLeod* [1985] discusses the Alldredge analysis and concludes with support for the internal interpretation.

In summary, measurements of large-scale, quasi-stationary electric fields at the Earth's surface can potentially provide independent (of magnetic measurements) information on poloidal electrical fields at the core-mantle boundary. A review of the few measurements which have been reported in the literature to date that attempt to address this problem suggest that the toroidal and poloidal magnetic fields at the core boundary are likely to be comparable in magnitude. The measurements to date also are consistent with *Roberts and Lowes* [1961] conclusion that thermoelectric emfs at the core-mantle boundary do not contribute appreciably to the observed poloidal magnetic field.

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