16 Telluric Currents: The Natural Environment and Interactions with Man-made Systems

LOUIS J. LANZEROTTI
AT&T Bell Laboratories

GIOVANNI P. GREGORI
Istituto di Fisica dell'Atmosfera, Rome

INTRODUCTION

Telluric currents consist of both the natural electric currents flowing within the Earth, including the oceans, and the electric currents originating from man-made systems. Telluric currents could also be considered to include geodynamo currents, i.e., the electric currents that are presumed to flow in the Earth's core and are responsible for the generation of the "permanent" geomagnetic field. This review excludes geodynamo considerations from its purview.

There has been an evolution (see Appendix) in the terminology in the English-language scientific literature related to telluric currents. A common former term used for telluric currents has been "Earth currents," a term that was widely used by Chapman and Bartels (1940) in their classic work, whereas Price (1967) preferred "telluric currents." A difference between the two terms can be recognized in reading historical papers: an impression is obtained that Earth's currents was the name applied to the natural currents (or, more properly, voltages) that are measured between two electrodes which are grounded at some distance apart. Independent of the cause, the observed current was termed an Earth's current. It later became evident that electric currents also flow in seawater. Therefore, the term telluric currents can be interpreted to include currents flowing both within the solid Earth and within the seas and oceans. However, we note that Earth currents and ocean currents do not form independent electric-current systems. On the contrary, leakage currents exist between continental areas and oceans (see, e.g., references in Gregori and Lanzerotti, 1982; Jones, 1983). In the early French and Italian scientific literature on the subject, however, the term telluric (derived from the Latin *tellus*, for Earth) was always used (e.g., Blavier, 1884; Battelli, 1888; Moureaux, 1896).

The fundamental causes of telluric currents are now believed to be understood. They are produced either through electromagnetic induction by the time-varying, external-origin geomagnetic field or whenever a conducting body (such as seawater) moves (because of tides or other reason) across the Earth's permanent magnetic field. Both causes produce telluric currents, which, in turn, produce magnetic fields of their own—fields that add to the external origin geomagnetic field and produce a feedback on the ionosphere current system (a feedback that, however, is negligible; see, e.g., Malin, 1970).

The complexities associated with telluric currents arise from the complexities in the external sources and in the conductivity structure of the Earth itself. Such complexities have led earlier workers to make statements such as "the simple laws of electromagnetic induction do not fully explain the cause of geoelectric and geomagnetic activity" (Sanders, 1961), while Winckler *et al.*, (1959), in discussing a 2650-V drop across a transatlantic cable produced during a magnetic storm (see below) concluded " . . . either the current circuit [in the Atlantic] is in the horizontal plane or the currents are not the result of the induced emf."

The mathematical modeling of telluric currents, unlike the understanding of their physical causes, is still far from a satisfactory solution. As far as Earth currents are concerned, the investigations have been for the most part carried out on a local or limited regional scale.

In contrast, the understanding of oceanic telluric currents (which cover a considerable fraction of the Earth's surface) has, since the Ashour (1950) estimate of their decay time in an ocean (order of a few hours), undergone substantial progress. The state of the art of ocean-current modeling now takes into account coastlines, although the ocean bottom is usually assumed flat—either nonconducting (although with a conducting mantle; see e.g., Parkinson, 1975; Hobbs and Brignall, 1976; Hobbs and Dawes, 1980; Beamish *et al.*, 1980; Fainberg, 1980, and references therein) or conducting (Hewson-Browne, 1981; Hewson-Browne and Kendall, 1981; Kendall and Quinney, 1983). The ocean currents and their related geomagnetic effects have been investigated by, for example, Barber and Longuet-Higgins (1948), Fraser (1965), Peckover (1973), Klein *et al.*, (1975), and Semevskiy *et al.* (1978). Malin (1970, 1973), in considering the lunar tidal harmonic component M_2 (which is the most important one both in the atmosphere and in the sea, with a period of half a lunar day), succeeded in separating the effect of direct electromagnetic induction from the ionosphere from the currents produced by oceanic tidal flow. He assumed that the geomagnetic variation associated with the tidal component should always be observed, independent of local time, whereas the ionosphere component should be negligible at midnight. In fact, he found that at Irkutsk, the geomagnetic observatory farthest from any ocean, the ocean-produced effect is negligible, unlike the situation at several other observatories closer to a coast, where the ocean component is present.

No equivalently sophisticated modeling, even for long-period geomagnetic variations, can usually be found for Earth currents. This situation exists principally because of the frustrating indeterminacies introduced by local Earth conductivity anomalies. The basic difficulty arises because of the nonuniqueness of the "inversion problem," that is, the nonuniqueness of the evaluation of the underground conductivity structure in terms of the surface geoelectromagnetic recordings. Therefore, the problem is usually tackled in terms of the "forward problem": an external-origin electromagnetic field is assumed to impinge on an underground conducting structure of given geometrical shape, with only the conductivities left to be optimized by a numerical fitting of the model with the actual observational records. The procedure can be worked out only for reasonably simple geometrical shapes (Porstendorfer, 1976) for the conducting bodies, which implies substantial limitations to any attempt to extend such investigations to wider spatial scales (see e.g., Rokityansky, 1982; Hohmann, 1983; Parker, 1983; Varentsov, 1983).

In terms of planetary-scale currents, Gish (1936a, 1936b) presented the results of Figure 16.1, which he deduced for the daytime western hemisphere from diurnal variation (24-h period) recordings of orthogonal Earth current measurements collected during the second International Polar Year (1932-1933) at a number of sites around the world. The directions of current flow were determined by taking the vector sum of the N-S and E-W currents measured at the various sites. Large errors could be expected because of the sparse number of stations and the need, therefore, for large interpolations.

A more recent picture has been provided by Matsushita and Maeda (1965a, 1965b; see also Matsushita, 1967) from analyses of the worldwide geomagnetic field on a planetary scale. These authors performed a standard separation (by means of Gauss' spherical harmonic expansion) of the external- and internal-origin field. Some of the results are presented in Figure 16.2. Notice the obvious, substantial differences compared to the currents of Figure 16.1. However, even the more recent work is obviously unable to recognize the effects, where important, of localized anomalous conductors, such as mid-oceanic ridges, or even the differences between ocean basins and continents. In fact, spherical harmonics vary too smoothly to be able to account for such localized features, particularly if a reasonably limited number of terms is used in the expansion (for recent reviews of spherical harmonic techniques, see Winch, 1981; Fainberg, 1983).

The first 75 to 100 years of Earth current work produced considerable debate as to causes and disagreements among researchers as to the magnitude of the effect at given times. Gish (1936a, 1936b) noted that better agreement between independent measurements often occurred when relatively long lengths of wire were used. Today it is clear that such a situation could easily arise from experimental procedures such as improper grounding of a wire and an insufficiently high impedance in the measuring system (e.g., see Hessler, 1974). For example, in the work of Airy (1868) the wires were grounded to water pipes, which themselves obviously

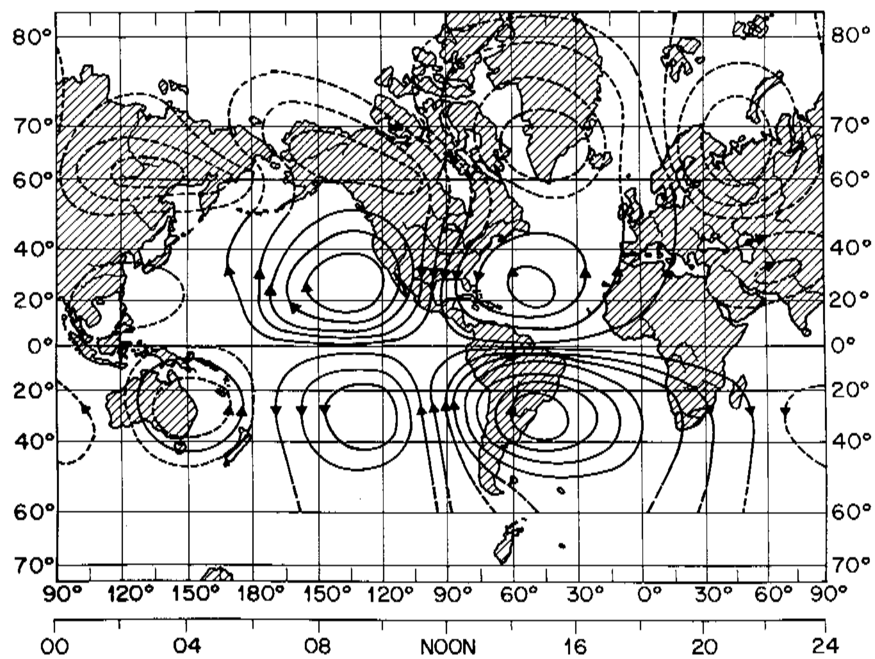


FIGURE 16.1 Planetary-scale distribution of telluric currents according to Gish (1936a, 1936b) at 1800 GMT.

could carry currents flowing in the entire region over which the relatively short lengths of wire extended. In this case, the pipe network was the receiving "antenna," even more than the lengths of wire. Recent evidence of the effect of telluric currents, integrated over a planetary scale, has been provided by analysis of MAGSAT data. Langel (1982) reported an analysis of the data in terms of separation, by spherical harmonic expansion, of the external- and internal-origin geomagnetic field. The analysis was done for different sets of data, depending on the value of the Dst index (a measure of the particle ring current in the Earth's magnetosphere and, therefore, of the level of disturbance of the geomagnetic field). Figures 16.3(a) and 16.3(b) show that the lowest order and degree terms (i.e., dipole terms), denoted g_1^0 and q_1^0 (external and internal, respectively) change with the level of Dst. The internal term increases with decreasing Dst, unlike g_1^0, a consequence of the fact that induced currents must flow in the direction opposite to the inducing currents.

Summarizing, accurate knowledge of telluric current patterns in the Earth on a planetary scale still remains a basically open problem even though the subject has a long history. In addition to the actual role of ocean water and sediments, largely unknown is the influence of localized conductivity anomalies (such as fold belts, mid-oceanic ridges, and trenches and subduction zones) on such patterns. The current patterns will obviously be different for different periods of the external inducing field. The higher-frequency patterns will be highly time variable because of the temporal and spatial variability of the external-origin fields, variabilities that are not yet amenable to accurate predictive modeling. Nevertheless, given all the foregoing caveats, we present in the following sections additional discussions of many of the relevant issues, as well as some implications for practical concerns.

THE NATURAL ENVIRONMENT

The Physical Problem: Hydrology, Geology, Geothermics, and Tectonics

Except during a lightning strike to Earth, essentially negligible electric current flows between the air and the ground (integrated over the Earth, the fair-weather current amounts to some 1000-2000 A). Therefore, the Earth's surface is a natural surface across which electromagnetic coupling occurs via an electromagnetic field. This implies that it is possible in many cases to treat the coupling problem in terms of scalar potentials (at least for frequencies lower than those used in audio magnetotelluric studies). An attempt by Berdichevsky and Fainberg (1972, 1974) to evaluate, on a global scale, possible currents between ground and air suffered large uncertainties from the approximations used. As noted briefly in the Introduction, the cause of telluric currents is either electromagnetic induction by the time-varying geomagnetic field produced by the ionosphere and/or magnetosphere or by water movement across the permanent

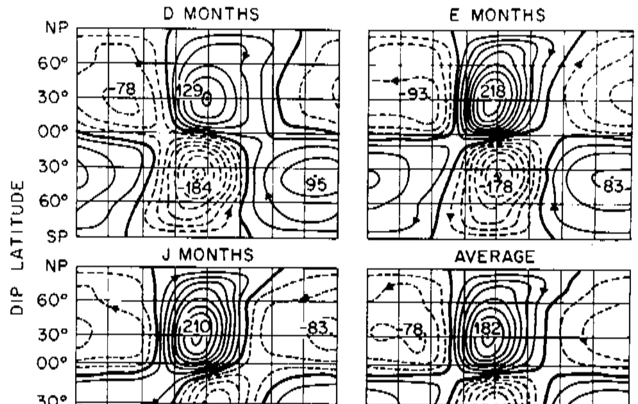


FIGURE 16.2 (a) External *Sq* current systems averaged worldwide for *D* months (northern winter; top left), *E* months (equinox, top right), and *J* months (northern summer, bottom left), and their yearly average (bottom right). The current intensity between two consecutive lines is 25×10^3 A; the thick solid curves indicate the zero-intensity lines. The numbers near the central dots are the total current intensities of these vortices in units of 10 A. (b) Internal *Sq* current systems averaged worldwide for *D* months (top left), *E* months (top right), and *J* months (bottom left), and their yearly average (bottom right). Notice the disagreement with Figure 16.1; the rotational senses of the vortices are opposite. This figure adapted from Matsushita (1967).

geomagnetic field. Considering only the former cause, the longer the period of the time-varying field, the greater the depth in the Earth where the induced currents can be expected to flow. A quantitative criterion can be given in terms of electromagnetic induction in a half-space of uniform conductivity (note that this is a highly idealized case that practically never occurs in reality). The "skin depth" (i.e., the depth at which the external field is damped by a factor $1/e$) is given by $S = 0.5\,(T/\sigma)^{0.5}$ km, where is the conductivity in mhos/meter and T is the period of the variation in seconds. A signal with period of about 24 h is generally believed to have a skin depth of 600 to 800 km (Hutton, 1976; Gough and Ingham, 1983). (The skin-depth only provides, however, a rough approximation of the depth at which actual telluric currents of a given period are flowing. In fact, the actual conductivity structure underground is most often a matter of considerable indeterminacy.) Saltwater has a conductivity of about 4 mhos/m, hydrated sediments have a conductivity of about 0.1 mho/m, and dry rock has a conductivity of about 0.0001 mho/m. Practically all the materials of the usual geologic environment (see, e.g., ACRES, 1975; Keller, 1966) can be placed between these extremes. Nomograms by which T, σ, and S can be evaluated for different materials and for the "actual" Earth are shown in Figure 16.4. The conductivity of water is largely affected by salinity (and to a minor extent by temperature). The conductivity of soil is largely affected by the state of hydration. Porous materials and sediments can easily be hydrated (see below) by considerable amounts. Hence it might eventually be possible, by electromagnetic means, to distinguish materials of equal density but with different porosities, and hence different hydration (and electrical conductivities), that cannot be distinguished by seismic techniques.

The distributions of sediments, particularly important for shorter-period variations, should be considered on local or regional scales, because minor details in the distributions can be relevant to telluric current flow. A worldwide pattern of sediments has been given by Hopkins (reproduced in Green, 1977, and in Gregori and Lanzerotti, 1982). Fainberg (1980) provided a worldwide model map of the total conductivity of the water shell plus sedimentary cover [Figure 16.5(a)]. Such a map is the result of a more detailed mapping given by Fainberg and Sidorov (1978). For example, Figure 16.5(b) shows the conductivity profile for Europe. Clearly shown are the sedimentary structures responsible for the North German conductivity anomaly and for the channeling in the Seine Basin. The North German anomaly, with a depth-integrated conductivity >3000 mhos, is equivalent to ≳750 m of seawater.

Another physical factor affecting conductivity, and thus telluric currents, is temperature. Since the temperature increases with depth in the Earth, the conductivity is higher with increasing depth. However, the effect is not uniform; the heat flux through the Earth's surface is greater in certain regions than in others, providing thermal anomalies. Whenever a larger geothermal flux

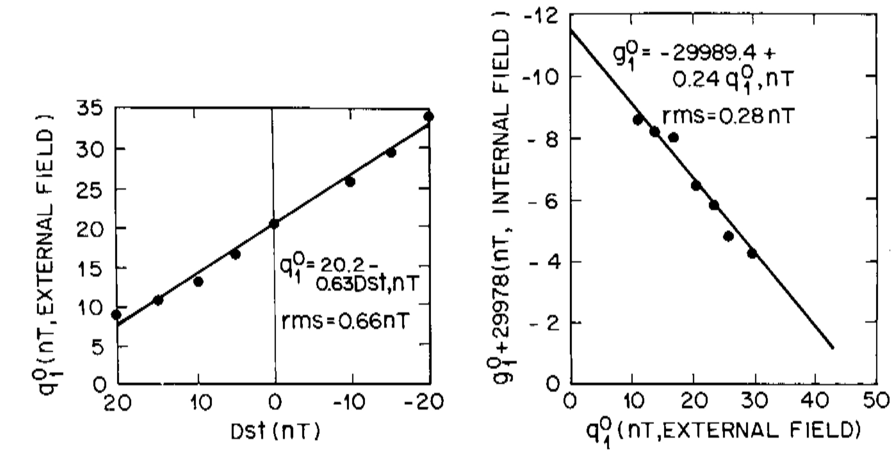
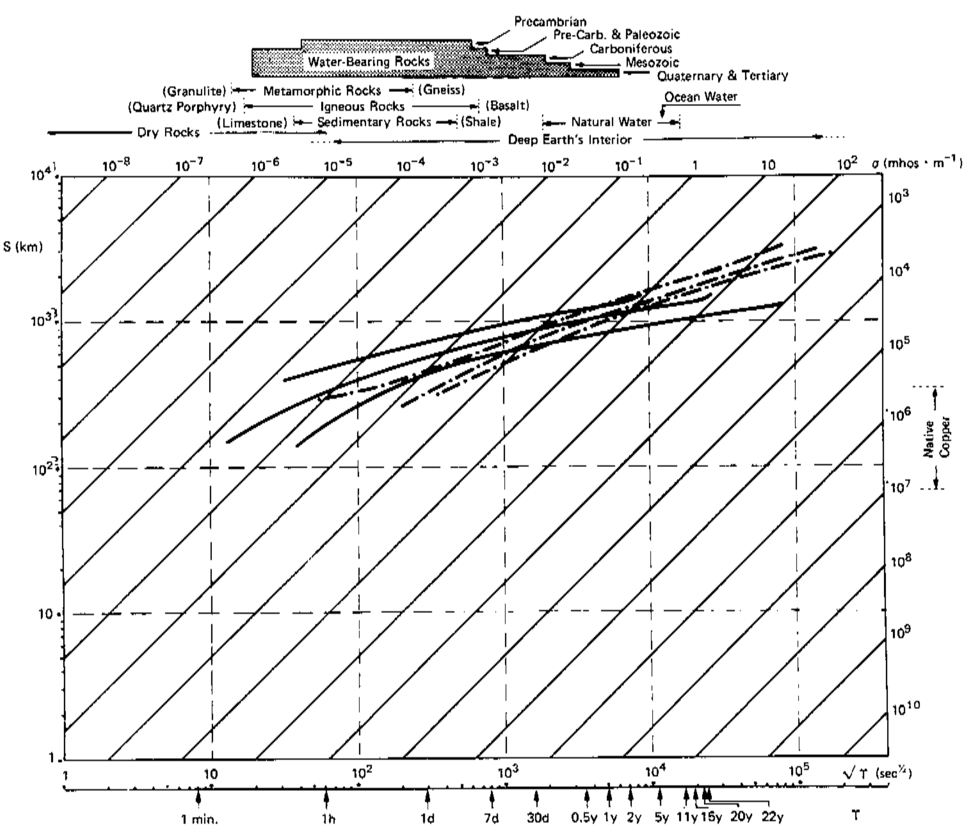


FIGURE 16.3 (a) The spherical harmonic coefficient of lowest degree and order describing the magnetic field originating external to the Earth, as a function of the global Dst index used to describe temporal variations of the equatorial horizontal magnetic field relative to magnetically quiet days. (b) The spherical harmonic coefficient of lowest degree and order describing the field originating within the Earth as a function of the lowest degree and order magnetic-field coefficient describing the magnetic field originating external to the Earth (adapted from Langel, 1982).

occurs, there is an upward warping of isothermal surfaces. In such a case, telluric currents of a given period will flow in shallower layers. A worldwide mapping of the geothermal flux averaged over a 5° × 5° mesh (Figure 16.6) has been provided by Chapman and Pollack (1975). (This map has largely been obtained using about 5000 direct borehole measurements and, where unavoidable, indirect information. For example, since the heat flow from the ocean floor is a well-defined function of the floor's age, the flow can be approximated even when it has not been directly measured. Analogously, a different function relates the continental heat flow to age.)

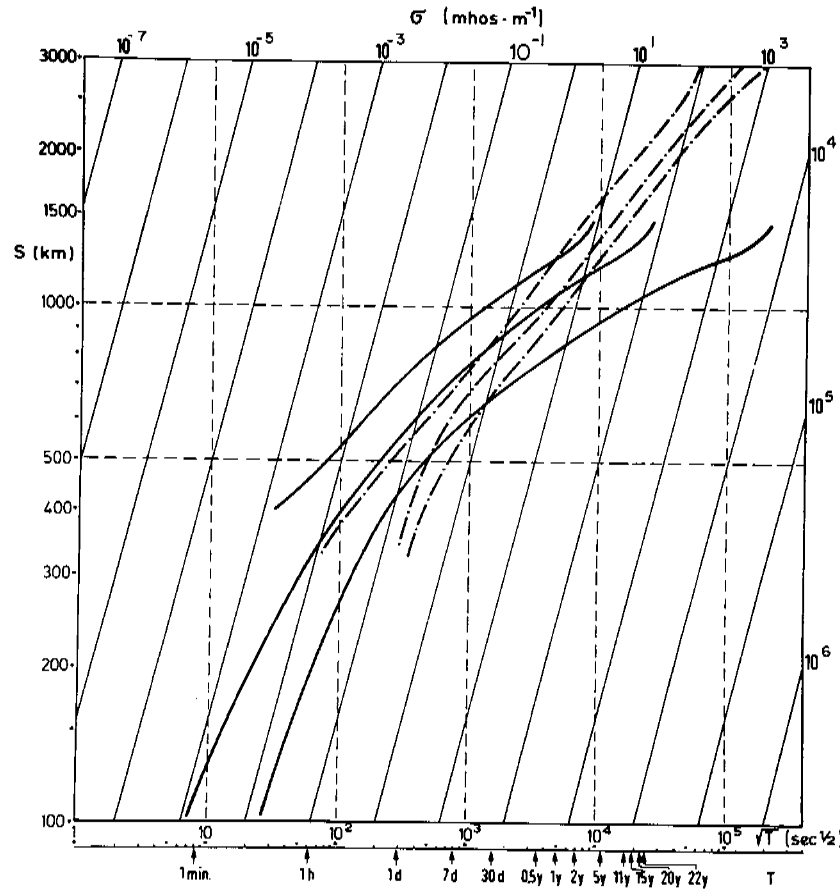
Three additional aspects of the conductivity structure of the Earth affect the flow of telluric currents—spatial gradients, temporal variations, and channeling.

The spatial gradients of telluric currents strongly depend, in shallow layers, on geochemical composition,



(a)

(b)



(c)

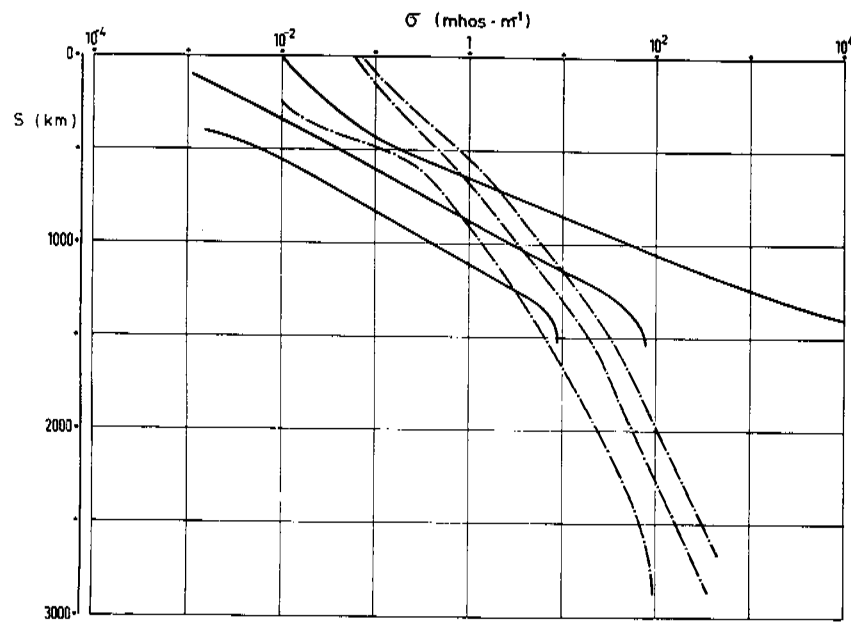
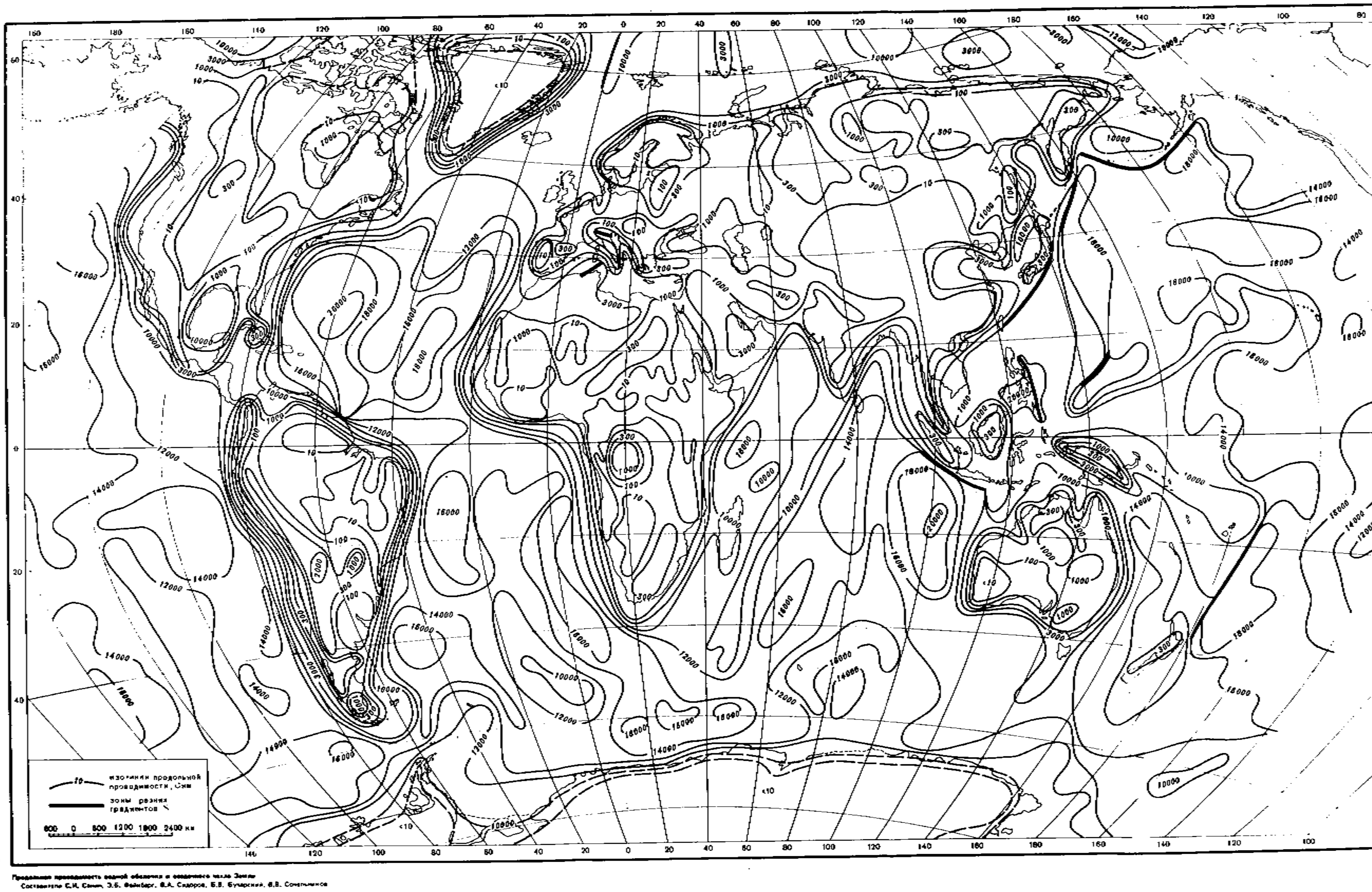
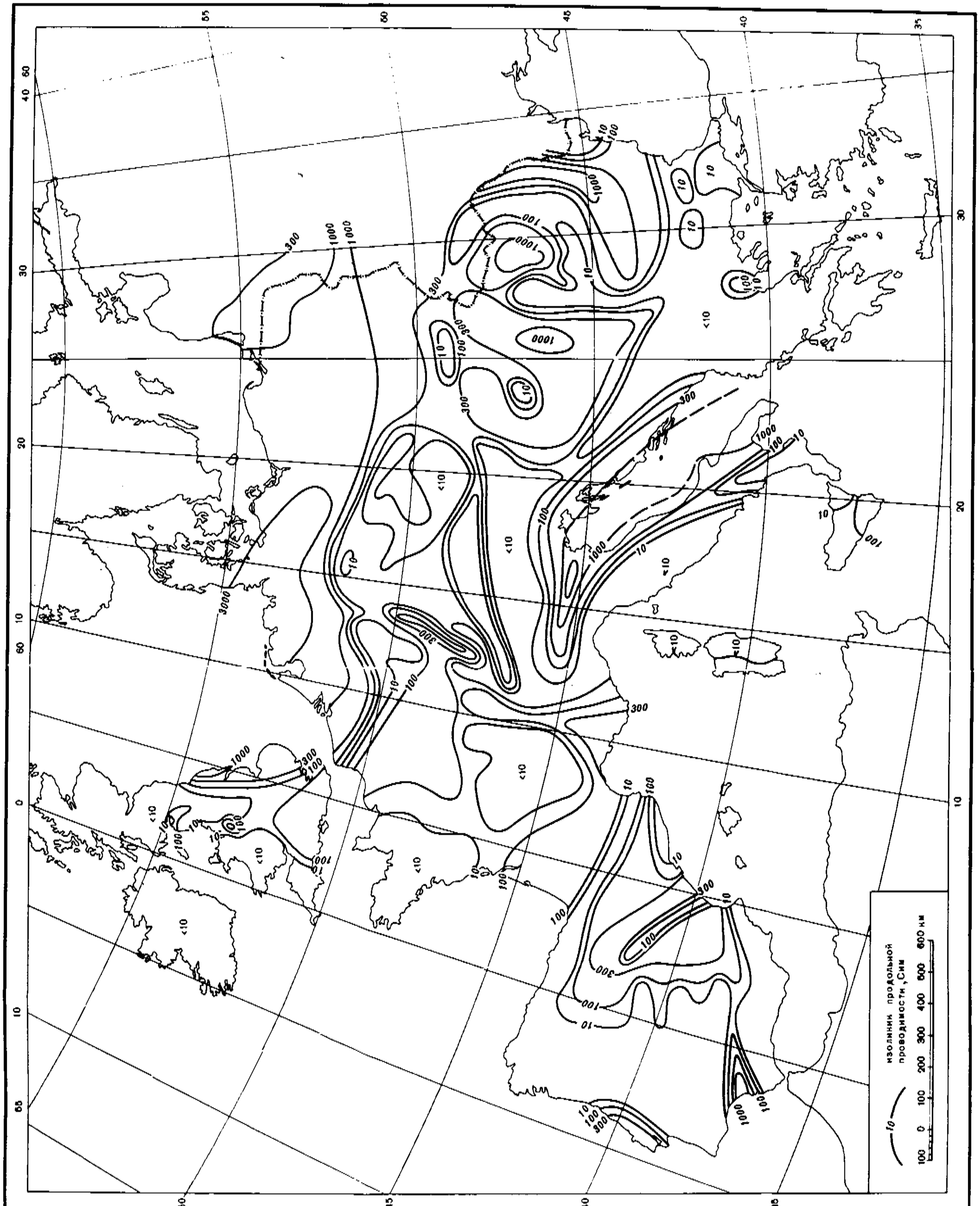


FIGURE 16.4 (a) Skin-depth nomogram, indicating depth probed as a function of period and material conductivity. Representative materials for given conductivities are shown, taken from the ACRES report (1975), which was adapted from Keller (1966). The central solid line represents the skin depth estimate for the actual Earth, assuming a planar half-space of uniform conductivity equal to the conductivity of the lowest evaluated depth of penetration; the upper and lower solid lines are explained below. The central line represents a lower limit on the depth. The almost equivalent dot-dashed lines have been drawn using the model of Achace *et al.* (1981). (b) Expanded version of the central portion of (a), detailing the depth range 100 km $\leq S \leq$ 3000 km. (c) Profiles of the conductivity of the Earth versus depth: full line, according to Rokityansky (1982); dash-dot line according to Achace *et al.* (1981). The lines above and below the estimated average profiles are indicative of the 95 percentile probability error distribution for the data of Rokityansky and of some level of uncertainty in the case of Achace *et al.* Rokityansky shows that practically all of the previous estimates of such a profile by different authors basically fall within his limits.



(a)

FIGURE 16.5 (a) Model maps of total conductivity of the water shell plus sedimentary cover. The isolines give the depth-integrated conductivity in units of mhos. The exceptionally solid lines are regions of rapid gradients in conductivity. From Fainberg and Sidorov (1978). (b) Expanded view of the European sector, from Fainberg and Sidorov (1978), where expanded models for other regions of the world are also provided.



(b)

Продольная проводимость осадочного чехла Западной Европы

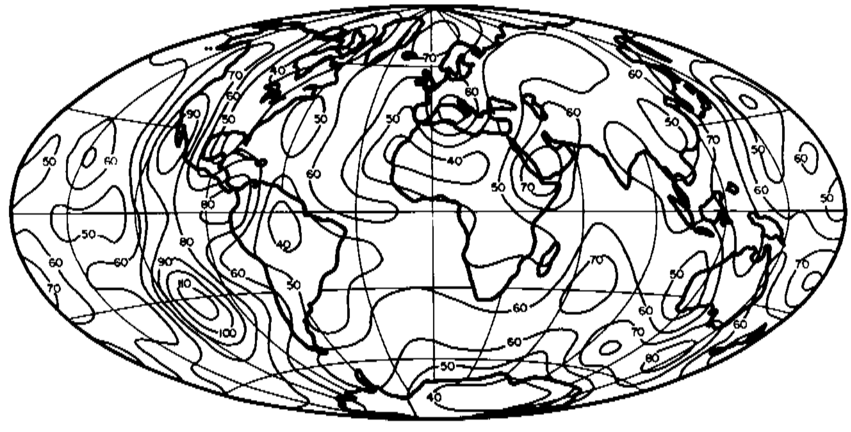


FIGURE 16.6 Spherical harmonic representation (degree 12) of global heat flow from observations supplemented by predictor. Heat-flow contour lines are in milliwatts per square centimeter. Adapted from Chapman and Pollack (1975).

geological structure, and hydration. [Hydration in this context can be taken just in terms of water content (producing an increase in conductivity) or in terms of the formation of particular compounds (clathrate hydrates) that can decrease the conductivity (although there are no reports of this in the telluric current literature); see Miller (1974).] Deeper in the Earth, it is believed that a more or less thick layer of dry rocks (having reduced conductivity) is further underlain by layers of increasing conductivity, which is a function of the increasing temperature with depth. In such deep layers it has generally been assumed that the Earth becomes increasingly homogeneous with greater depth. More realistically, however, the increasing difficulty (if not impossibility) of recognizing spatial gradients at greater depths must be acknowledged. Differently stated, telluric currents as a means of remote sensing of the underground conductivity provide ever-diminishing spatial (horizontal) resolution with depth.

The problem of spatial gradients of the telluric currents is also related to the state of knowledge of the spatial gradients of the external-origin inducing field. In fact, the diurnal and the lunar variation fields (*Sq* and *L* fields, respectively) have a planetary scale, albeit showing strong spatial gradients related to the auroral and equatorial electrojets for quiet conditions (e.g., Schlapp, 1968; Riddihough, 1969; Greener and Schlapp, 1979). For disturbed conditions, the planetary-scale description still plays a relevant, though not singular, role (e.g., Sato, 1965; Campbell, 1976). Therefore, the external-inducing source at these low frequencies can be approximately described in terms of a planetary-scale field, occasionally with strong spatial gradients.

On the contrary, for higher frequencies (magnetic storms, geomagnetic pulsations) the source can often appear quite localized (see, e.g., Davidson and Heirtzler, 1968; Lanzerotti *et al.*, 1977; Southwood and Hughes, 1978; Reiff, 1983) and is highly time dependent as well. At the Earth's surface the spatial extent of the source for pulsations (period of a few to a few hundreds seconds) is believed to be not smaller than the height of the ionosphere.

Temporal variations in the Earth's conductivity structure can be caused by such effects as seasonal climatic changes affecting water salinity and temperature, ice extension, permafrost and hydration content, and tectonic processes. The tectonic processes can be either slow (i.e., those involving the geologic time scale), intermediate (as in earthquake precursors; e.g., Honkura, 1981), or rapid (as in volcanoes).

Channeling of telluric currents in specific, higher-conductivity regions is an actively debated area at present. Some recent research papers, without presumption of completeness, include Lilley and Woods (1978), Babour and Mosnier (1980), De Laurier *et al.* (1980), Miyakoshi (1980), Srivastava and Abbas (1980), Woods and Lilley (1980), Camfield (1981), Chan *et al.* (1981a, 1981b), Kirkwood *et al.* (1981), Kurtz *et al.* (1981), Sik *et al.* (1981), Srivastava (1981), Thakur *et al.* (1981), Booker and Hensel (1982), DeBeer *et al.* (1982), Le Mouël and Menvielle (1982), Nienaber *et al.* (1982), and Summers (1982); see also extensive review and discussion by Jones (1983). The issue revolves around the interpretation of the measured telluric currents. Should the measurements at some given site be interpreted in terms of electromagnetic induction on a local (or in any case on a small-scale) spatial extent, or should they be considered as the result of a large-scale (i.e., regional, continental, or planetary scale) induction phenomenon, whereby telluric currents are channeled from more remote areas within some relevant conducting body not far away from the recording site? While specific cases can be discussed (such as the North German anomaly; see Appendix), a generally valid reply is difficult to give basically because (1) the planetary-scale response of the actual Earth in terms of telluric currents is poorly known and (2) the temporal and spatial scale of the external-origin inducing field is often poorly known, particularly for shorter-period variations represented by magnetic storms and geomagnetic pulsations.

It is interesting to note that the current channeling was addressed early on in studies of telluric currents. Varley (1873) discussed current channeling from the sea in telegraph wires between the coastal town of Ipswich and London. He also claimed that enhanced currents were seen in the line between Glasgow and Edinburgh, which connected the sea across the British Isle, as compared with a line solely on land.

Summarizing, telluric currents depend on several physical parameters and, if properly interpreted, can be used for studies of the underground electrical structure at both shallow and great depths. It is important for telluric current studies to take into more explicit account the relations of measured currents to the specific tectonic and geomorphological features of the regions under study. Approaches toward such a viewpoint have been presented recently by Hermance (1983). In general, such investigations can best be tackled by means of large arrays of instrumentation (Alabi, 1983).

Shallow Telluric Currents

Effects on shallow telluric currents (generally shorter period) can be found whenever a mineral has some remarkably different electrical conductivity compared with that of the surrounding materials. This gives rise to a localized conductivity anomaly that can be studied by means of a dense network of recording instruments. Shallow currents have also been reported in several sedimentary basins, such as in the Seine Basin and in the northern German anomaly (see Appendix; for other references see, e.g., Gregori and Lanzerotti, 1982). Shallow telluric currents are responsible for a component of the coast effect or magnetic signals, where the geometrical orientation of the magnetic variations at higher frequencies are correlated with the shape of the coast. The coast effect has been reviewed by Fischer (1979), Parkinson and Jones (1979), and Gregori and Lanzerotti (1979b).

The difference between shallow and deep effects (the latter arising from local tectonic features) has been shown by Honkura (1974) for the Japanese islands (Figure 16.7). At shorter periods, when the skin depth is shallower, the coast effect reflects the coast shape. At longer periods, electromagnetic induction evidence suggests a dependence on the downward bending of the lithospheric slab where it approaches the Japanese subduction zone. Similar effects have been reported by Honkura *et al.* (1981) for a small island in the Philippine Sea ("regular" coast effect) and by Beamish (1982) for the island of South Georgia (Scotia Arc, South Atlantic). The threshold period discriminating between shallow and deep effects appears to be about 20 min in the Japanese area, a result obtained from a reinterpretation by Gregori and Lanzerotti (1982) of data published by Yoshimatsu (1964).

Deep Telluric Currents

The best recognized, by seismic waves, underground discontinuity—the Moho (see, e.g., global map presented by Soller *et al.*, 1982)—has no obvious correspondence in geoelectromagnetic phenomena. In fact, the behavior of deep telluric currents is largely controlled by the shape of the isotherms. An idea of the trend of such isotherm surfaces is given by Figure 16.8, which plots isocontours of the thickness of the lithosphere (Chapman and Pollack, 1977), based on the heat-flux results of Figure 16.6. Chapman and Pollack (1977) derived the lithosphere results by determining the depth at which both continental and oceanic geotherms intersect the mantle solidus. They showed this to be a consistent estimator of the depth to the top of the seismic low-velocity channel or of the thickness of the high-velocity lid overlying the channel. They identified the lid as synonymous with the lithosphere.

A similar discussion, limited to the Soviet Union, is given by Cermak (1982). Oxburgh (1981) presented a critical discussion of the method employed for such analyses. For the sake of completeness, however, it should be noted that the concept of the lithosphere is actually more complicated. Depending on the experimental observations used, four different definitions can be distinguished: the elastic or flexural, the thermal, the seismic, and the chemical or mineralogical (U.S. Geodynamics Committee, 1983; Anderson, 1984; Maxwell, 1984). In the context of telluric currents, the thermal structure of the deep Earth is likely the most relevant factor, with the chemical/mineralogical being the second. Hence, in this simple context, Figure 16.8 can provide an idea of the depth where a high electrical conductivity can be expected at a given site. A very general and approximate statement is that the thickness estimates of Figure 16.8 are in reasonable agreement with geomagnetic depth-sounding and magnetotelluric estimates of the depth of the "ultimate conductor": about 200 km below continents (cratons), about 100 km under stable continental areas, about 60-70 under rifts and grabens, and about 10-20 km (or even shallower) under volcanic areas and mid-ocean ridges. [A warning must be given

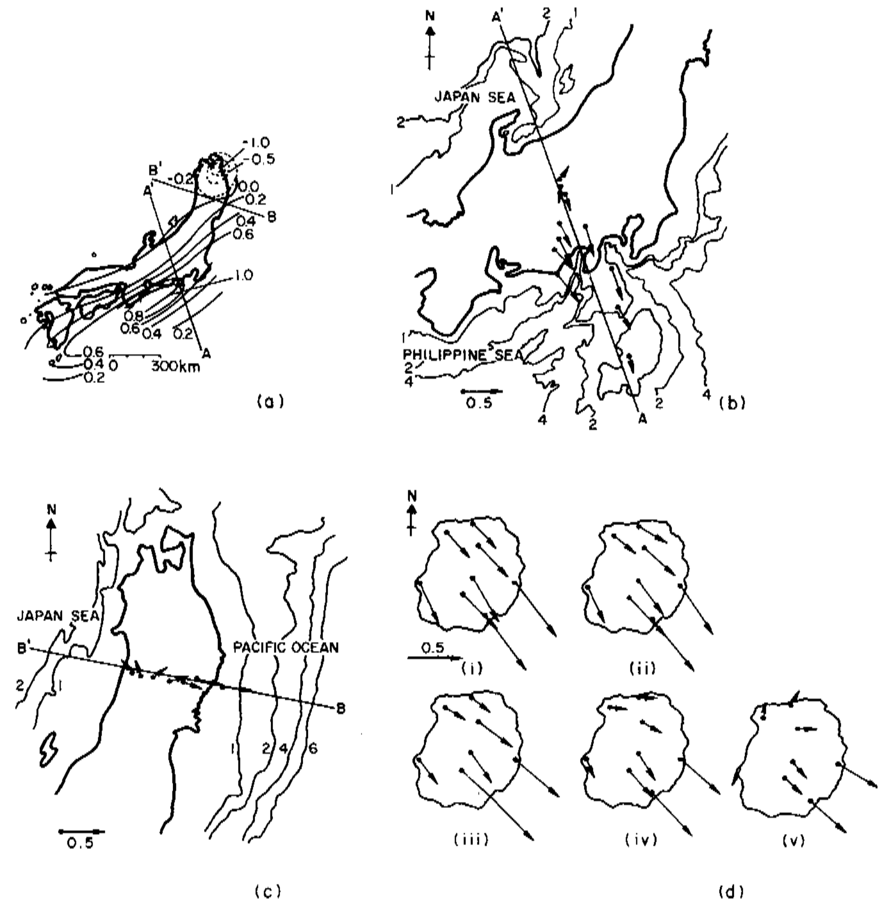


FIGURE 16.7 (a) The $\Delta Z/\Delta H$ value distribution in Japan for geomagnetic variations corresponding to geomagnetic bays. The profiles AA′ and BB′ have been investigated in detail, and their results are shown in the subsequent figures. (b) Parkinson vectors along the profile AA′ of part (a), for geomagnetic variations with period of 60 min. Contours indicate the sea depth in 10^3 m. The Parkinson vectors are consistent with an interpretation in terms of an asthenosphere bending and deepening in the subduction zone. (c) The same as for profile AA′ in part (b), but referring to the profile BB′. The downward bending of the asthenosphere in the subduction zone appears much less pronounced in this region. (d) Parkinson vectors on the Miyakejima island for periods (a) 120, (b) 60, (c) 30, (d) 15, and (e) 5 min, respectively. The coast effect is quite evident at the shorter periods, while at the longer periods the effect of the bending of the asthenosphere is predominant over the coast effect.

The vectors appearing in the (b), (c), and (d) sections of the figure are "Parkinson arrows" or "vectors," defined in the following manner. Consider the deepest surface layer to which the incident electromagnetic wave of a given period can penetrate. Consider a plane (the "Parkinson plane") tangent to such a surface, directly beneath a given recording site. Construct a line perpendicular to this plane and oriented downward. Project this line in the horizontal plane: this is the direction of the arrow. The length of the arrow is equal to the sine of the tilt of the Parkinson plane with respect to the horizontal plane. Therefore, a vanishing Parkinson arrow implies a horizontal Parkinson plane, a unit length arrow implies a vertical Parkinson plane. A "normal" coast effect on an island shows that Parkinson arrows point outward from the island. (For other details on "induction arrows" refer to the review by Gregori and Lanzerotti, 1980.) Figure is adapted from Honkura (1974).

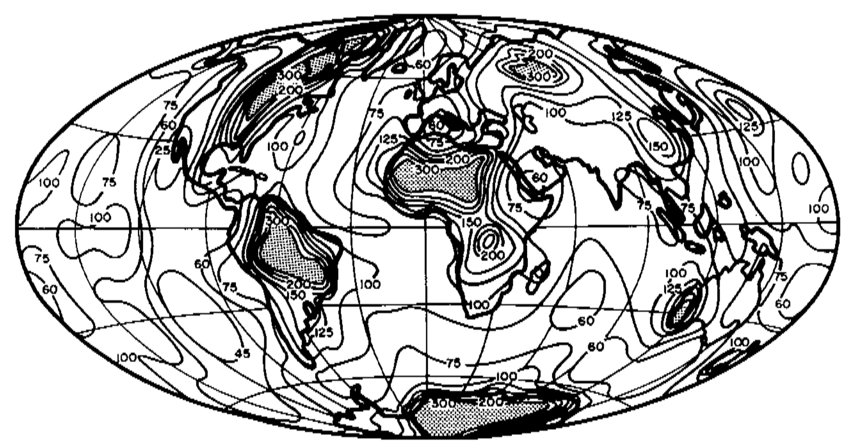


FIGURE 16.8 Thickness of the lithosphere derived from a spherical harmonic (12 degree) representation of the global heat flow (see Figure 16.6) and continental and oceanic geotherm families. Contours are in kilometers, with variable intervals. From Chapman and Pollack (1977).

here, however, that these depths are very approximate; the actual structures are generally much more differentiated and complex; see, e.g., Hermance (1983).]

The problem of the deep electrical conductivity structure of the Earth has usually been treated in terms of a concentric spherical shell model of the Earth, where each shell has a uniform electrical conductivity. The interested reader may refer to such classical treatments as Chapter XXII of Chapman and Bartels (1940), Rikitake (1966), Rokityansky (1982), or Parkinson (1982) (a more concise treatment can be found in Price, 1967). A simple but effective procedure was proposed by Schmucker (1970) whereby the Earth is simplified to a two-layer body having an insulating outer layer underlain by a conductor (he considered both flat and spherical Earth models). Using only the ratio of the horizontal to the vertical component of the geomagnetic field (at a prechosen frequency), Schmucker (1970) provided simple formulas by which the thickness of the insulating layer and the electrical conductivity of the underlying conductor can be promptly evaluated. By considering fields of different frequencies it is possible to evaluate different estimates of depth and conductivity. This "Schmucker inversion" technique, which often appears to agree with results obtained by means of other, more involved, methods of handling geomagnetic data, is a simple way of treating the inversion problem—a difficult and much debated problem (e.g., Rokityansky, 1982; Hohmann, 1983; Parker, 1983; Varentsov, 1983; Gough and Ingram, 1983; Berdichevsky and Zhdanov, 1984).

INTERACTIONS OF TELLURIC CURRENTS WITH MAN-MADE SYSTEMS

The natural telluric current environment can significantly affect man-made systems. Conversely, human technology can "pollute" the natural telluric current environment. The mechanisms by which these interactions occur, as well as their modeling, are far from being understood satisfactorily and comprehensively. Geophysicists have often viewed such interactions as an unwanted, unnatural nuisance. Engineers have almost always been concerned with thresholds of system reliability and with a system's capability to react positively to any sudden change in the natural environment, always on a strict basis of yield/cost ratio. Moreover, technological improvements have been progressively introduced within systems to ensure a higher and higher reliability (e.g., Axe, 1968; Anderson, 1979), so that it becomes difficult to compare effects observed on different systems in different years.

Seldomly have man-made systems been viewed as scientific instruments that are useful for studying the natural environment. Often a man-made system can be considered part of the natural environment itself. Geophysicists can then imagine such large man-made tools as similar to specifically designed measuring instruments that, unlike laboratory instruments that are normally presumed to negligibly affect the system, actually interfere with the natural phenomena, often quite seriously. Such huge and expensive man-made systems can allow, in principle, some complex experiments and measurements, which otherwise could not be carried out. For this reason this topic has particular scientific value, much beyond a matter of scientific curiosity or of a more or less minor nuisance affecting the operation of huge engineering systems.

The literature on the subject tends to be rather sparse. However, five principal areas of interest can be considered. These are discussed below; some of this material has been previously reviewed elsewhere (Axe, 1968; Lanzerotti, 1979a, 1979b, 1979c, 1983; Paulikas and Lanzerotti, 1982).

Communication Cables

Historically, this is the best investigated and documented effect of telluric currents on technological systems. In fact, after the lightning rod, the telegraph was essentially the earliest of man-made electromagnetic devices in use. Subsequently, telegraph lines have been progressively supplanted by telephone lines, and submarine cables have supplanted the former radio links between the telephone networks of different continents (e.g., Blackwell, 1928; Bown, 1930, 1937; Schelleng, 1930). Even with the advent of communication satellites, cable systems are still of major economic importance for long-distance communications.

The first detection of effects on a telegraph wire dates back to the years 1847-1852. The first observations appear to be from England by Barlow (1849). As stated by Prescott (1866):

> M. Matteucci had the opportunity of observing this magnetic influence under a new and remarkable form. He saw, during the appearance of the aurora borealis of November 17, 1848, the soft iron armatures employed in the electric telegraph between Florence and Pisa remain attached to their electromagnetics, as if the latter were powerfully magnetized, without, however, the apparatus being in action, and without the currents in the battery being set in action. This singular effect ceases with the aurora, and the telegraphs, as well as the batteries, could operate anew, without having suffered any alteration. Mr. Highton also observed in England a very decided

action of the aurora borealis, November 17, 1848. The magnetized needle was always driven toward the same side, even with much force. But it is in our own country that the action of the aurora upon the telegraph-wires has been the most remarkable. . . . In September, 1851, . . . there was remarkable aurora, which took complete possession of all the telegraph lines in New England and prevented any business from being transacted during its continuance.

The days between August 28 and September 2, 1859, were also quite remarkable, not only for some wonderful auroral displays (Clement, 1860; Hansteen, 1860; Prescott, 1860, 1866). Clement's (1860) book had a self-explanatory title: *The Great Northern Light on the Night before 29 August 1859 and the Confusion of the Telegraph in North America and Europe.* According to Chapman and Bartels (1940), this aurora was seen in the Atlantic at a latitude as low as 14° N, while in France 800 V were induced on a wire over a distance of 600 km. From Prescott (1866):

We have, however, the second yet more wonderful effects of the aurora upon the wires; namely, *the use of auroral current for transmitting and receiving telegraphic dispatches.* This almost incredible feat was accomplished . . . on the wires of the American Telegraph Company between Boston and Portland, upon the wires of the Old Colony and Fall River Railroad Company between South Braintree and Fall River, and upon other lines in various parts of the country. . . . Such was the state of the line on the September 2nd, 1859, when for more than one hour they held communication over the wires with the aid of celestial batteries alone.

Other studies of historical interest on telluric currents in communication cables are mentioned in the Appendix.

In 1910 work was begun in Norway by Carl Störmer of measuring the height of polar aurorae (Störmer, 1955). Störmer used photographs taken simultaneously from two sites separated by a few tens of kilometers. He was able to send a message of alert to his co-workers about an imminent night of photographic work whenever he measured disturbances in the local telegraph wires.

A geomagnetic storm in Sweden in May 1921 (Germaine, 1942; Sanders, 1961) produced voltages of 6.3 to 20 V/km (i.e., 1 kV or more over 100 to 200 km, with 2.5 A, while the threshold for serious troubles was 15 mA). A large magnetic storm on April 16, 1938, produced potentials of several hundred volts over local wires in Norway (Chapman and Bartels, 1940).

On March 24, 1940 (Germaine, 1942; Harang, 1951; Brooks, 1959; Sanders, 1961), a geomagnetic storm damaged the Norwegian wirelines (≲50-60 V/km, ~600 V, >4 A), while in the United States, more than 500 V were estimated to have occurred along some lines. Reports from two sites near Tromso, Norway, stated

. . . Sparks and permanent arcs were formed in the coupling racks and watch had to be kept during the night to prevent fire breaking out. . . . One line was connected to earth through a 2 mm thick copper wire, which at once got red hot, corresponding to a current more than 10 amps (Harang, 1951).

In the second half of the nineteenth century, Earth currents in submarine cables were rather extensively investigated. Saunders (1880, 1881) and Graves (1873) reported some of their work, which included a cable between Suez and Aden and a cable between Valentia and Newfoundland. Wollaston (1881) concluded that his current measurements on a submarine cable across the English Channel resulted from tidal currents and related an 1851 conversation with Faraday on the matter. The latter was quoted as quite enthused about this confirmation of his earlier predictions.

Axe (1968) listed several geomagnetic storm-induced effects on submarine cables occurring in 1957-1967 (total voltage drops range from 50 V to 2700 V for the different occurrences). The largest voltage drop (Figure 16.9) occurred across a transatlantic cable (equivalent to 0.75 V/km) at the time of the huge storm on February 11, 1958, which produced a well-known spectacular auroral display down to low latitudes (Brooks, 1959; Winckler *et al.*, 1959; Sanders, 1961; Akasofu *et al.*, 1966). It is noteworthy that "the cable to Hawaii which originates about 140 miles north of San Francisco exhibited no major voltage swings" (Winckler *et al.*, 1959).

A major geomagnetic event on August 4, 1972, caused the outage of a continental cable in the midwestern United States. The outage has been investigated (Anderson *et al.*, 1974; Anderson, 1979) by modeling the tel-

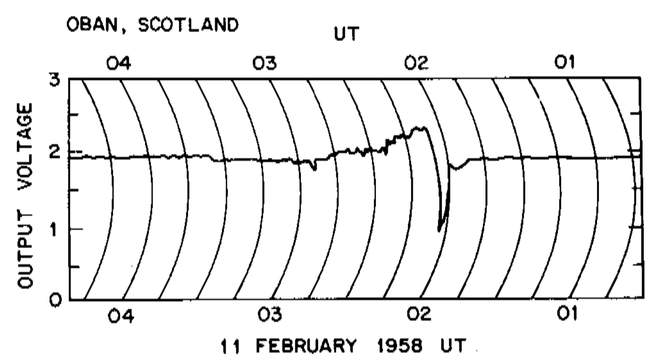


FIGURE 16.9 Output voltage of the power-feed equipment at the Oban, Scotland, end of the Oban-Clareville, Newfoundland, cable. The voltage variation in North America was somewhat larger, leading to a total variation of about 2700 V across the cable. From Axe (1968).

luric currents in terms of a compressed magnetosphere with magnetopause and magnetosphere currents electromagnetically inducing over a three-layer conducting Earth.

Summarizing, shutdowns in both land and sea cables, as well as fires, have been caused by telluric currents induced by geomagnetic storms, and suitable precautions have to be taken (Root, 1979) in order to attempt to avoid them.

A singular example of man-made telluric current "pollution" occurred when a high-altitude nuclear bomb test produced perturbations in the Earth's radiation belts and geomagnetic field. As recounted in Axe (1968):

> The disturbance was just detectable on the power-feeding voltage and current recorder charts on the Australia-New Zealand, United Kingdom-Sweden and Bournemouth-Jersey systems. On a circuit originally set up on the Donaghadee-Port Kail No. 3 cable for the measurement of voltage due to water flow, the disturbance was clearly recorded.

The data at the time of the event are shown in Figure 16.10 (Axe, 1968).

All the effects considered above refer to electromagnetic induction from ionospheric and magnetospheric variations. However, there are also effects on submarine communication cables related to water flows (tidal and otherwise). The problem has been extensively reviewed by Meloni *et al.* (1983); see later section. Less dramatic, although relevant, man-induced telluric current perturbations on land cables should be expected in heavily industrialized or populated areas (e.g., Kovalevskiy *et al.*, 1961).

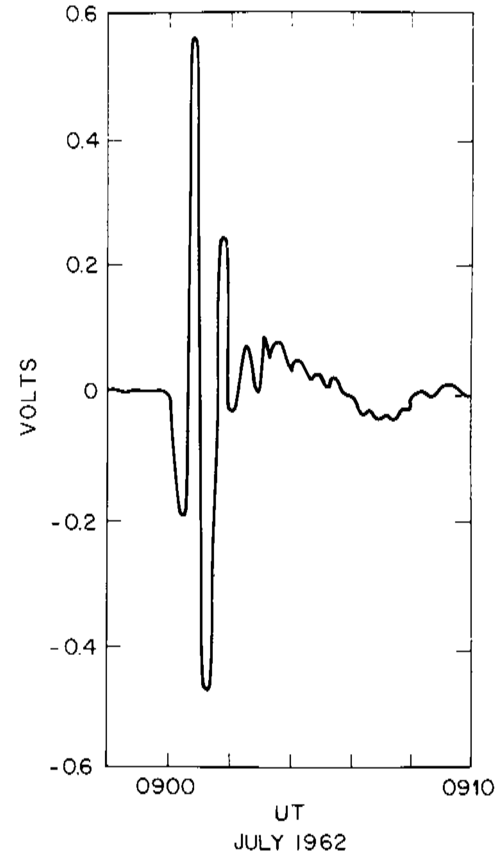


FIGURE 16.10 Effect of the Starfish explosion measured on the center-conductor voltage of the Donaghadee-Kail (Irish Sea) number 3 cable. From Axe (1968).

Powerlines

The historical record of powerlines being greatly distributed or completely disrupted by geomagnetic storms appears somewhat less detailed than that for communications cables. One interruption of service occurred on March 24, 1940, in New England, New York, eastern Pennsylvania, Minnesota, Quebec, and Ontario (Davidson, 1940; Brooks, 1959). As well, during the great geomagnetic storm of February 11, 1958, the Toronto area suffered from a blackout produced by a geomagnetic storm. Currents up to about 100 A were induced in some northern latitude transformers during the great storm of August 4, 1972 (McKinnon, 1972). Induced currents on power systems in the auroral zone have been discussed by Aspnes *et al.* (1981) and Akasofu and Aspnes (1982; see Figure 16.11). Some of the most detailed investigations aimed at establishing engineering relations for power systems have been carried out by

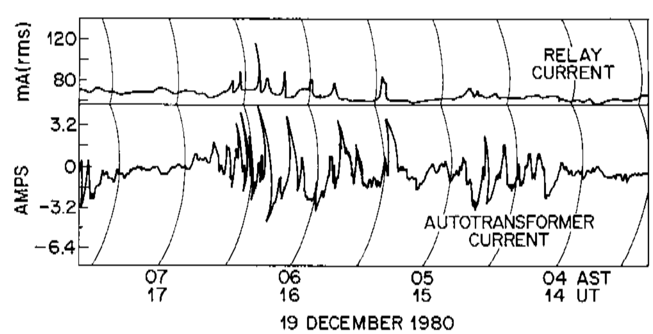


FIGURE 16.11 Simultaneous recordings of geomagnetic induction effects observed as current surges in a positive relay system and an auto transformer in a power substation near Fairbanks, Alaska, on December 19, 1980 (from Akasofu and Aspnes, 1982).

Albertson and Van Baelen (1970), Albertson *et al.* (1970, 1973, 1974), ACRES (1975) (see also references therein), Boerner *et al.* (1983), and Pirjola (1983).

The geomagnetic currents induced in a power system can produce problems of several different types (Albertson *et al.*, 1973, 1974; review by Williams, 1979). First, the arbitrary differential relay operation in power distribution systems during geomagnetic storms can produce a judgmental problem; system operators are unsure of whether the malfunctioning relay indication is an induced-current effect in a transformer or a real transformer malfunction. Second, the currents actually induced in the winding of a power transformer can result in half-cycle saturation of the transformer core. This saturation can produce fluctuations in the transformer operation itself. This local heating can greatly shorten the lifetime of a transformer.

Summarizing, the effects of induced telluric currents on power systems produce outages as well as damages to expensive transformers. Gorely and Uvarov (1981) estimated that in the Norilsk region (Siberia) up to tens of amperes can be expected on powerlines of 100 to 150 km length. Since 500-kV transformers capable of withstanding even 3 to 4 A without saturating appear to cause problems for manufacturing (Sebesta, 1979), a way of avoiding such serious damage is to use powerlines of limited total length (e.g., Akasofu and Merritt, 1979, suggest no more than 500 km for Alaska). Pirjola (1983), from measurements made at four locations in Finland, concluded that currents of the order of 100 A lasting about 1 h should damage transformers.

Pipelines

Varley (1873) reported that large Earth currents on a short length of telegraph cable in London appear to have been related to currents flowing on large, nearby gas pipelines. Studies of induced telluric currents on pipelines took renewed importance when the long, Trans-Alaskan pipeline (1280 km long) was built. The effects of telluric currents appear to be of most importance in affecting electronic equipment related to operational monitoring and corrosion control rather than in producing specific serious corrosion problems.

Viewing a pipeline as a man-made part of the natural environment, it is noteworthy to mention the 30-A current reported by Peabody (1979) to cross the Panama Isthmus, from ocean to ocean, a current that also changes direction. Such specific currents can produce corrosion failures at some ocean terminals of the pipelines, even before the pipeline is in operation. Such problems can be avoided most simply by suitable separate ground connections (Peabody, 1979).

The Alaskan pipeline has been the subject of careful investigations, principally because of its location across the auroral zone (Hessler, 1974). Campbell (1978, 1979, 1980) and Campbell and Zimmerman (1980) provided a comprehensive account of the problem and concluded that the current I expected to flow within the pipeline is related to the geomagnetic index A_p by the linear relationship $I = 5.0\ A_p - 0.7$. Based on the statistics of occurrence of the A_p index (larger for greater geomagnetic activity), at least once a year about 600 A should be observed, 800 A should be observed at least once every 2 years, and 1200 A should be observed at least once every 5 years. The dimensions of the Alaskan pipeline (diameter of ~ 1.22 m, a mean wall thickness of ~ 1.30 cm, a resistance per unit length of $\sim 2.81 \times 10^{-6}\ \Omega$/m, and an end-to-end total resistance of 3.6 Ω; Campbell, 1979) suggest that it is a large man-made conductor that is capable of significantly affecting the local natural regime of telluric currents.

Railways

Pollution by artificially produced telluric currents associated with railway operations have been investigated from several viewpoints. Burbank (1905) reported the effects in 1890 of the South London Electric Railway on the Earth current records being made at Greenwich. The nuisance for geomagnetic observations of telluric currents associated with return currents from dc electrified railways has perhaps been the most widely investigated effect (La Cour and Hoge, 1937; Rössiger, 1942; Yanagihara and Oshima, 1953; Mikerina, 1962; Yanagihara and Yokouchi, 1965; Yanagihara, 1977). The spatial extent within the ground of telluric currents from railway operations has been investigated by Kovalevskiy *et al.* (1961) in the southern Urals. They detected telluric current pulses with periods between a few seconds and 20 minutes and amplitudes of about 0.5 to 3 V/km. They found the effects to drop off rapidly within 10 to 15 km from the railway, although still being dominant over natural telluric currents at 30 km, and still detectable at 60 km (where the measurements stopped). Meunier (1969), following a previous investigation by Dupouy (1950), detected telluric current effects related to a specific operation (lowering and raising the pantograph) of the Paris-Toulouse railway at 115 km distance from the railroad. This effect, in fact, can sometimes be detected on the magnetograms from the Chambon-la-Forêt observatory. An example of the effect is shown in Figure 16.12. Jones and Kelly (1966) detected Earth currents in Montreal, clearly correlated with a dc powered railway some 20 km distant.

F. Molina (private communication, Osservatorio

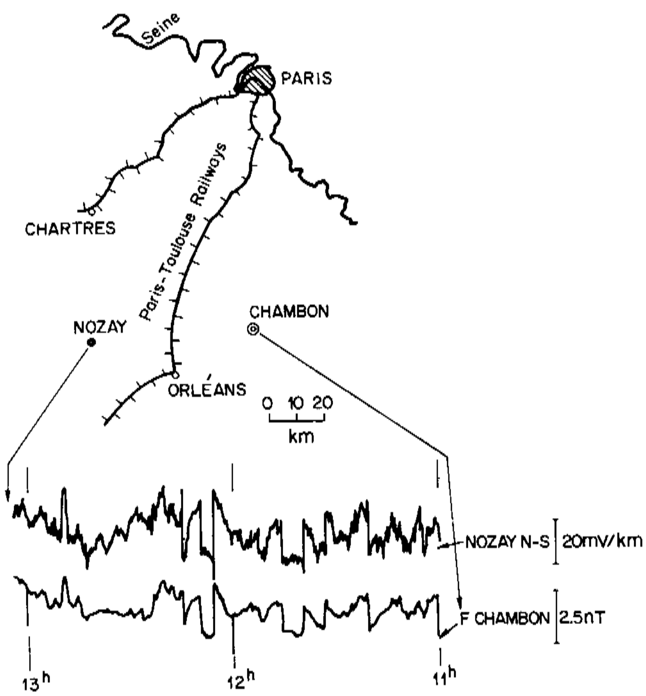


FIGURE 16.12 Artificial Earth currents (north-south direction) measured (Fournier and Rossignol, 1974) at Nozay (France) and concurrent fluctuations in the total magnetic field measured at Chambon-la-Forêt, on opposite sides of the Paris-Toulouse electrified railway line.

Geofisico Monte Parzio, Italy), in close examination of standard magnetogram records from the observatory at L'Aquila, has found a difference in the width of the trace depending on whether the Italian railways are on strike or not. In the former case, the Z-component trace is about a factor of 2 less thick than during normal operations. The noise introduced appears to be about 0.5 nT. The closest railway is about 30 km away.

A most impressive telluric current effect (Fraser-Smith and Coates, 1978; Fraser-Smith, 1981) in the San Francisco Bay area has been produced by BART (the San Francisco Bay Area Rapid Transit system). ULF waves (frequency less than 5 Hz) are observed, having energy at a frequency predominantly below about 0.3 Hz. Their amplitudes are at least ten times greater than the natural background environment, i.e., they are comparable with the levels reached during great geomagnetic storms. The effect originated by BART appears to occur over an area of about 100 km^2.

A similar effect has been detected by Lowes (1982) in Newcastle upon Tyne (U.K.), produced by the dc rapid transit underground railway system. F. J. Lowes (University of Newcastle upon Tyne, private communication, 1985) also noted that when the system starts up in the morning he can follow individual train movements over about 12 km of track before there is too much superimposition of the signals.

Corrosion

Corrosion in buried metal structures (in addition to pipelines) is significantly enhanced by the occurrence of telluric currents, presumably via electrolytic processes. This is a well-known phenomenon to people routinely working on repairs of telephone cables or of pipes (for water or otherwise). Severe damage comes mainly from man-made telluric currents when the conductors are buried close to dc electrified railways or tramways. A simple insulating coating, provided that it has no holes, appears to be the best protection. The problem is discussed to some extent by Peabody (1979). A much older reference (given by Kovalevskiy *et al.*, 1961) is Tsikerman (1960). The problem can exist also for buried powerlines that have, unlike aerial power lines, some relevant problems of heat flow (Salvage, 1975).

APPLICATIONS OF TELLURIC CURRENT MEASUREMENTS

Listing all possible applications of telluric current measurements is presumptuous and almost impossible. A tentative scheme is given here, which, perhaps, can provide a first approach to such a complex topic.

Detection of Electromagnetic Signals from Space

The Earth (including natural conductivity structures and man-made systems, such as communication cables and powerlines) can be treated as a receiving antenna, useful for monitoring the external origin electromagnetic fields. Communication cables of varying length can provide information on the spatial scale as a function of frequency of the external signal. See Meloni *et al.* (1983) for additional discussions of this point.

Prospecting of Underground Structures

Prospecting of underground structures is the most developed application of telluric currents. The methodology is quite extensive. There are two principal approaches, viz., Magneto-Tellurics (MT), which uses measurements of the two horizontal components of both the geomagnetic and the geoelectric fields, and Geomagnetic Depth Sounding (GDS), which uses measurements of all three components of the geomagnetic field. "Active" methods (see, e.g., Keller, 1976; Ward, 1983) make use of man-made electromagnetic fields. Such methods are well suited for shallow prospecting but can hardly be applied to deeper layers, because of the skin-depth phenomenon. Such required long-period electromagnetic waves cannot be generated practically. Long powerlines have been used for generating electromagnetic induction fields for prospecting purposes (e.g., Gill and MacDonald, 1967).

A distinction should be made between prospecting techniques that use the static geomagnetic field of the Earth and techniques that use electromagnetic induction effects. In handling the standard aeromagnetic and oceanographic magnetic surveys, whose purposes are to understand the static fields, the time-varying fields recorded at a ground-based site "close" to the area of the survey must be subtracted from the air or the ocean signal. This introduces some errors, whose actual values are often difficult to estimate (e.g., Reford, 1979). The time-varying component from such surveys can be used for geomagnetic depth-sounding studies (Gregori and Lanzerotti, 1979a).

Deep-Earth Studies

Telluric currents are likely eventually to be important tools for prospecting the deep structure of the Earth, thus providing valuable complementary information to that provided by seismic waves. A great advantage of GDS methods is that, while many studies concentrate on magnetic storm events, the studies can also be carried out using inducing signals during more quiet times, signals that are always in existence. The use of induced currents from natural electromagnetic waves for deep-Earth research is being pursued actively in a number of countries, particularly the Soviet Union. Recent reviews include books by Rokityansky (1982), Patra and Mallick (1980), Parkinson (1982), and Berdichevsky and Zhdanov (1984).

Tidal Phenomena and Water Flows

There are three types of tides: atmospheric, oceanic, and solid Earth. Atmospheric tides generate a large part of the external-origin inducing field of long period; oceanic tides produce a time-varying geomagnetic field associated with water flows; and solid-Earth tides can similarly produce a geomagnetic field because they can produce an eventual water flow that will produce a magnetic field. Theoretical and observational aspects of the phenomena have been discussed by Meloni *et al.* (1983).

Within the past decade extensive use of shorter undersea cables (such as those across the Dover Strait; e.g., Prandle, 1978) has been made for studies of tidal oscillations and water flow. Cables across the Irish Sea have been used for such studies (for example, Prandle and Harrison, 1975; Prandle, 1979). Geomagnetic disturbances can affect the measurement capabilities and, hence, results of such a cable-monitoring system. The data presented in Figure 16.13 are from chart recordings of the cable voltage on the Donoghadee-Port Patrick cable on a day of geomagnetic disturbances (Prandle and Harrison, 1975). The low-frequency variation in the voltage, spanning the record, is produced by tidal flow. The higher-frequency variations, produced by geomagnetic storm induction of currents in the cable, obscure the variations in such a manner that the data cannot be used reliably for water-flow information on such a day.

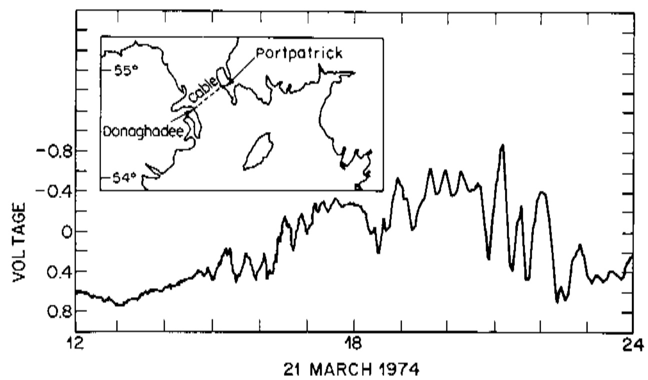


FIGURE 16.13 Cable voltage on the Donaghadee-Port Patrick cable on a geomagnetically disturbed day (from Prandle and Harrison, 1975).

Earlier, Wertheim (1954), in studying water flow across the Florida straits using the Key West-Havana cable, found occasional rapid variations in the cable voltage. He attributed these to geomagnetic effects and tried to model them using magnetometer data from the San Juan Observatory. Recent work in studies of the Florida current were reported by Larsen and Sanford (1985).

Earth's Astronomical Motion

The variation in the length of the day and the displacements of the positions of the geographic poles are among the most precise and fascinating topics in geophysics and have now become a vast discipline. The problem, however, of a possible role of telluric currents in producing a braking or an acceleration in the Earth's rotation or in displacing the Earth's poles appears still basically unsolved and/or is not considered important by many. This is discussed in some detail by Meloni *et al.* (1983) (and references therein), where also the possible use of a transatlantic communication cable is discussed as a possible experimental device to detect such an effect.

Earthquakes, Volcanoes, and Geodynamics

Since telluric currents are excellently suited for deep-Earth investigations, they are in principle also suitable for monitoring long-scale time variations as well. The most investigated aspect from this viewpoint is concerned with earthquake precursors (e.g., review by Honkura, 1981, and references therein). A clear distinction should be made among three different, possible types of phenomena: (1) geomagnetic effects that can presumably be said to be "very shallow" and are likely related to piezomagnetism, following changes in local stresses in the upper crust, which is an effect strictly local and can completely change in a distance of a few kilometers or less; (2) "shallow" effects that can be detected by ground resistivity changes or by suitably short-period MT or GDS investigations; and (3) "deep" or "very deep" effects that can be most suitably detected by means of long-period GDS investigations. This latter category of effects is more strictly related to telluric currents than are the first two types of effect.

Additional possible applications in this area include (1) slowly varying effects correlated with geodynamic and tectonic features, (2) shallow effects related to magma migration in volcanic areas, and (3) the monitoring of temporal variations in underground structures as related to fluid extraction (or reinjection). The shallow effects could, however, possibly be better detected by use of man-made electromagnetic fields than by means of natural fields. Telluric currents are also well suited for investigating ocean-bottom and geothermal areas (see Law, 1983; Berktold, 1983).

Communications

Within the last 10 to 15 years suggestions have been made that a natural waveguide in the Earth's crust, composed of the insulating layer of dry rocks sandwiched between the upper hydrated conducting and the underlying conducting hot layer, could be used for communication purposes. This suggestion, however, does not seem to have been followed by any known application. Existing literature is referenced in Gregori and Lanzerotti (1982). A practical problem is certainly concerned with the spatial nonuniformity of such a waveguide, the width and depth of which is undoubtedly widely varying (e.g, compare a cratonic area with a mid-oceanic ridge area) and is essentially unknown in many regions.

In a similar fashion, magma chambers in mid-oceanic ridges can be considered the natural "equivalent" of man-made submarine communication cables. The conductivities are such that the mid-Atlantic ridge is equivalent to about 1000 such cables in parallel (see Gregori and Lanzerotti, 1982).

An interesting communication experiment related to artificial telluric currents was reported by Fraser-Smith *et al.* (1977). They operated, as a transmitting antenna (using a simple car battery), a circuit loop composed of seawater encircling a small peninsula in a nearly enclosed area.

Biological Effects

The response of living species to electromagnetic fields (such fields being either responsible for, or a consequence of, telluric currents) is a difficult but important problem. Several examples discussed in the literature include the induced currents in a tree produced by geomagnetic fluctuations (Fraser-Smith, 1978) and the use of magnetic fields for orientation by aquatic bacteria (e.g., Blakemore, 1975) and by migrating birds (e.g., Moore, 1977; Larkin and Sutherland, 1977; Alerstam and Högstedt, 1983; Beason and Nichols, 1984). Telluric currents could play a role in some control of fish (e.g., Leggett, 1977; Kalmijn, 1978; Brown *et al.*, 1979; Fainberg, 1980; Fonarev, 1982). Magnetite crystals have been reported as isolated from a sinus in the yellowfin tuna (Walker *et al.*, 1984). Enhanced DNA synthesis has been reported for human fibroblasts exposed to magnetic-field fluctuations with frequencies and amplitudes similar to many geomagnetic occurrences (Liboff *et al.*, 1984). The entire area is fraught with controversy, particularly that related to magnetic effects, and has been reviewed by Parkinson (1982) and commented on by Thomson (1983).

CONCLUSIONS

Historically, telluric currents were intensively investigated in the second half of the nineteenth century, particularly because of their influences on long telegraph conductors (see Appendix). The intrinsic difficulties encountered in obtaining fundamental understanding, basically related to the several causes that can be coresponsible for the observed effects, discouraged geophysicists from pursuing such investigations vigorously. However, with respect to a century ago, large improvements have been made in a number of areas, including recording techniques, density of available observations, international data exchanges, computational facilities, mathematical methodologies, and general geophysical understanding. Hence, research in this area would appear to be poised for achieving significant new understanding.

Investigations using, and studying, the telluric currents suffer from three principal drawbacks: (a) the spatial coverage by the recording equipment is often too sparse compared to the extent and spatial gradients of the phenomena under investigation; (b) there is not general agreement on the experiment and analysis methodologies, often leading to difficulties when comparing the results from different investigations; and (c) the use, within the general understanding of deep geophysical structures, of the information provided by electromagnetic techniques is often neglected. It is hoped that these deficiences will be ameliorated in future telluric current work.

Telluric currents are a relevant part of our electromagnetic environment, both as a consequence of the time-varying natural electromagnetic field and as a consequence of moving seawater. Human interactions with telluric currents and their related effects are definitely important, even though such interactions are only incompletely understood. A considerable effort on geomagnetic source characteristics and Earth conductivity characteristics are required before a satisfactory and comprehensive understanding can be achieved. The critical role of telluric currents within the geophysical environment, encompassing such areas as the Earth's astronomical motion, to current channeling, to eventual implications for ocean-water motion, still appears as a challenging frontier. As well, further assessments must be made on the actual role of telluric currents, as well as of the geomagnetic field *in toto*, on biological systems. The field is multidisciplinary and fascinating. Substantial achievements can be expected in the near future.

ACKNOWLEDGMENTS

We thank the referees and F. J. Lowes for helpful comments and references.

REFERENCES

Achace, J., J. L. LeMouel, and V. Courtillot (1981). Long-period geomagnetic variations and mantle conductivity: An inversion using Bailey's method, *Geophys. J. R. Astron. Soc. 65*, 579-601.

ACRES Consulting Services Limited (1975). Study of the disruption of electric power systems by magnetic storms, *Earth Phys. Branch Open File 77-19*, Niagara Falls, Ontario, Department of Energy, Mines and Resources, Ottawa.

Airy, G. B. (1868). Comparison of magnetic disturbances recorded by self-registering magnetometers at the Royal Observatory, Greenwich, with magnetic disturbances described from the corresponding terrestrial galvanic currents recorded by the self-registering galvanometers of the Royal Observatory, *Phil. Trans. R. Soc. 158A*, 465-472.

Akasofu, S.-I., and J. D. Aspnes (1982). Auroral effects on power transmission line systems, *Nature 295*, 136-137.

Akasofu, S.-I., and R. P. Merritt (1979). Electric currents in power transmission line induced by auroral activity, *Nature 279*, 308-310.

Akasofu, S.-I., S. Chapman, and A. B. Meinel (1966). The aurora, *Handb. Phys. 49*(1), 1-158.

Alabi, A. D. (1983). Magnetometer array studies, *Geophys. Surv. 6*, 153-172.

Albertson, V. D., and J. A. Van Baelen (1970). Electric and magnetic fields at the Earth's surface due to auroral currents, *IEEE Trans. Power Appar. Syst. PAS-89*(4), 578-584.

Albertson, V. D., S. C. Tripathy, and R. E. Clayton (1970). Electric power systems and geomagnetic disturbances, in *Proceedings of Midwest Power Symposium*, October 29-30.

Albertson, V. D., J. M. Thorson, Jr., R. E. Clayton, and S. C. Tripathy (1973). Solar-induced currents in power systems: Causes and effects, *IEEE Trans. Power Appar. Syst. PAS-92*, 471-477.

Albertson, V. D., J. M. Thorson, Jr., and S. A. Miske, Jr. (1974). The effects of geomagnetic storms on electrical power systems, *IEEE Trans. Power Appar. Syst. PAS-93*, 1031-1044.

Alerstam, T., and G. Högstedt (1983). The role of the geomagnetic field in the development of birds' compass sense, *Nature 306*, 463-465.

Anderson, C. W. (1979). Magnetic storms and cable communications, in *Solar System Plasma Physics*, L. J. Lanzerotti, C. F. Kennel, and E. N. Parker, eds., North-Holland, Amsterdam, pp. 323-327.

Anderson, C. W., L. J. Lanzerotti, and C. G. Maclennan (1974). Outage of the L-4 system and the geomagnetic disturbances of August 4, 1972, *Bell Syst. Tech. J. 53*, 1817.

Anderson, D. L. (1984). The Earth as a planet: Paradigms and paradoxes, *Science 223*, 347-355.

Ashour, A. A. (1950). The induction of electric currents in a uniform circular disk, *Q. J. Mech. Appl. Math. 3*, 119-128.

Aspnes, J. D., R. D. Merritt, and S. I. Akasofu (1981). The effects of geomagnetically induced current on electric power systems, *Northern Eng. 13*(3), 34.

Axe, G. A. (1968). The effects of Earth's magnetism on submarine cables, *Electr. Eng. J. 61*(1), 37-43.

Babour, K., and J. Mosnier (1980). Direct determination of the characteristics of the currents responsible for the magnetic anomaly of the Rhinegraben, *Geophys. J. R. Astron. Soc. 60*, 327-331.

Barber, N., and M. S. Longuet-Higgins (1948). Water movements and Earth currents: Electrical and magnetic effects, *Nature 161*, 192-193.

Barlow, W. H. (1849). On the spontaneous electrical currents observed in the wires of the electric telegraph, *Phil. Trans. R. Soc. 61A*, 61-72.

Battelli, A. (1888). Sulle correnti telluriche, *Atti R. Accad. Naz. Lincei 4*, 25.

Beamish, D. (1982). Anomalous geomagnetic variations on the island of South Georgia, *J. Geomagn. Geoelectr. 34*, 479-496.

Beamish, D., R. C. Hewson-Browne, P. C. Kendall, S. R. C. Malin, and D. A. Quinney (1980). Induction in arbitrarily shaped oceans IV, Sq for a simple case, *Geophys. J. R. Astron. Soc. 60*, 435-443.

Beason, R. C., and J. E. Nichols (1984). Magnetic orientation and magnetically sensitive material in a transequatorial migratory bird, *Nature 309*, 151-153.

Berdichevsky, M. N., and E. B. Fainberg (1972). Possibility of experimental separation of the variable geomagnetic field into poloidal and toroidal parts, *Geomagn. Aeron. 12*, 826-830.

Berdichevsky, M. N., and E. B. Fainberg (1974). Separation of the field of Sq variations into poloidal and toroidal parts, *Geomagn. Aeron. 14*, 315-318.

Berdichevsky, M. N., and M. S. Zhdanov (1984). *Advanced Theory of Deep Geomagnetic Sounding*, Elsevier, Amsterdam, 408 pp.

Berktold, A. (1983). Electronmagnetic studies in geothermal regions, *Geophys. Surv. 6*, 173-200.

Blackwell, O. B. (1928). Transatlantic telephony—the technical problem, *Bell System Tech. J. 7*, 168-186.

Blakemore, R. P. (1975). Magnetoactive bacteria, *Science 190*, 377-379.

Blavier, E. E. (1884). Sur les courants telluriques, *C. R. Hebd. Séana Acad. Sci. 98*, 1043-1045.

Boerner, W.-M., J. B. Cole, W. R. Goddard, M. Z. Tarnawecky, L. Shafai, and D. H. Hall (1983). Impacts of solar and auroral storms on power line systems, *Space Sci. Rev. 35*, 195-205.

Booker, J. R., and G. Hensel (1982). Nature's hidden power line, *Sci. Digest 90*, 18.

Bown, R. (1930). Transoceanic telephone service—Short wave transmission, *Bell Syst. Tech. J. 9*, 258-269.

Bown, R. (1937). Transoceanic radiotelephone development, *Proc. IRE 25*, 1124-1135.

Brooks, J. (1959). A reporter at large: A subtle storm, *New Yorker* (Feb. 7), 39-69.

Brown, H. R., O. B. Ilyinsky, V. M., Muravejko, E. S. Corshkov, and G. A. Fonarev (1979). Evidence that geomagnetic variations can be detected by Lorenzian ampullae, *Nature 277*, 648-649.

Burbank, J. E. (1905). Earth-currents and a proposed method for their investigation, *Terr. Magn. Atmos. Electr. 10*, 23-49.

Camfield, P. A. (1981). Magnetometer array study in a tectonically active region of Quebec, Canada, *Geophys. J. R. Astron. Soc. 65*, 553-570.

Campbell, W. H. (1976). Spatial distribution of the geomagnetic spectral composition for disturbed days, *J. Geomagn. Geoelectr. 28*, 481-496.

Campbell, W. H. (1978). Induction of auroral zone electric currents within the Alaska pipeline, *Pure Appl. Geophys. 116*, 1143-1173.

Campbell, W. H. (1979). The Alaskan pipeline, in *Solar System Plasma Physics*, L. J. Lanzerotti, C. F. Kennel, and E. N. Parker, eds., North-Holland, Amsterdam, pp. 352-356.

Campbell, W. H. (1980). Observation of electric currents in the Alaska oil pipeline resulting from auroral electrojet current sources, *Geophys. J. R. Astron. Soc. 61*, 437-499.

Campbell, W. H., and J. E. Zimmerman (1980). Induced electric currents in the Alaskan oil pipeline measured by gradient fluxgate and Squid magnetometers, *IEEE Trans. Geosci. Electron. GE-18*, 244-250.

Cermak, V. (1982). A geothermal model of the lithosphere and a map of the thickness of the lithosphere on the territory of USSR, *Izv. Akad. Nauk SSR Ser. Phys. Solid Earth 18*, 18-27.

Chan, G. H., H. W. Dosso, and L. K. Law (1981a). Electromagnetic induction in the San Juan Bay region of Vancouver island, *Phys. Earth Planet. Inter. 27*, 114-121.

Chan, G. H., H. W. Dosso, and W. Nienaber (1981b). An analogue model study of electromagnetic induction in the Queen Charlotte Island region, *J. Geomagn. Geoelectr. 33*, 587-606.

Chapman, D. S., and H. N. Pollack (1975). Global heat flow: A new look, *Earth Planet. Sci. Lett. 28*, 23-22.

Chapman, D. S., and H. N. Pollack (1977). Regional isotherms and lithospheric thickness, *Geology 5*, 265-268.

Chapman, S., and J. Bartels (1940). *Geomagnetism* (2 volumes), Clarendon Press, Oxford, 1049 pp.

Clement, K. T. (1860). *Das grosse Nordlicht in der Nacht zum 29 August 1859 und die Telegraphenverwirrung in Nord-Amerika und Europa*, Hamburg, pp. 1-121.

Davidson, M. J., and J. R. Heirtzler (1968). Spatial coherence of geomagnetic rapid variations, *J. Geophys. Res. 73*, 2143-2162.

Davidson, W. F. (1940). The magnetic storm of March 24, 1940—effects in the power system, *Bull. Edison Electr. Inst. 365*.

DeBeer, J. H., R. M. J. Huyssen, S. J. Joubert, and J. S. V. Van Zijl (1982). Magnetometer array studies and deep Schlumberger sounding in the Damara orogenic belt, South West Africa, *Geophys. J. R. Astron. Soc. 70*, 11-23.

De Laurier, J. M., E. R. Niblett, F. Plet, and P. A. Camfield (1980). Geomagnetic depth sounding over the central Arctic islands, Canada, *Can. J. Earth Sci. 17*, 1642-1652.

Dupouy, G. (1950). Perturbation de champ magnétique terestre et des courants telluriques par les chemins de fer électrofiés, *Ann. Geophys. 6*, 18-50.

Fainberg, E. B. (1980). Electromagnetic induction in the world ocean, *Geophys. Surv. 4*, 157-171.

Fainberg, E. B. (1983). Global geomagnetic sounding, Preprint No. 50a, pp. 1-66, Izmiran, Moscow.

Fainberg, E. B., and W. A. Sidorov (1978). Integrated conductivity of the sedimentary cover and water shell of the Earth [in Russian], Izmiran, with 5 maps, Nauka, Moscow, pp. 1-11.

Fischer, G. (1979). Electromagnetic induction effects at an ocean coast, *Proc. IEEE 67*, 1050-1060.

Fonarev, G. A. (1982). Electromagnetic research in the ocean, *Geophys. Surv. 4*, 501-508.

Fournier, H., and J. C. Rossignol (1974). A magnetotelluric experiment in Nozay-en-Dunois (Eure-et-Loir, France): Results, interpretation and critical study, *Phys. Earth Planet. Inter. 8*, 13-18.

Fraser, D. C. (1965). Magnetic fields of ocean waves, *Nature 206*, 605-606.

Fraser-Smith, A. C. (1978). ULF tree potentials and geomagnetic pulsations, *Nature 271*, 641-642.

Fraser-Smith, A. C. (1981). *Adv. Space Res. 1*, 455.

Fraser-Smith, A. C., and D. B. Coates (1978). Large-amplitude ULF electromagnetic fields from BART, *Radio Sci. 13*, 661-668.

Fraser-Smith, A. C., O. G. Villard, Jr., and D. M. Dubenick (1977). A study of the "Peninsula method" for the controlled artificial generation of ULF waves in the ionosphere and magnetosphere, Technical Report No. 4207-7-SEL-77-041, Radioscience Laboratory, Stanford Electronics Labs., Stanford Univ., pp. 1-35.

Germaine, L. W. (1942). The magnetic storm of March 24, 1940—effects in the communication system, *Bull. Edison Electr. Inst.*, 367-368.

Gill, P. J., and W. J. P. MacDonald (1967). Large scale earth resistivity experiment in New Zealand, *Nature 216*, 1195-1197.

Gish, O. H. (1936a). Electrical messages from the Earth, their reception and interpretation, *J. Wash. Acad. Sci. 26*, 267-289.

Gish, O. H. (1936b). Electrical messages from the Earth, their reception and interpretation, *Sci. Mon. N.Y. 43*, 47-57.

Gorely, K. I., and O. I. Uvarov (1981). Currents of geomagnetic disturbances in power lines of the Norilsk district [in Russian], *Issled. Geomagn. Aeron. Fiz. Solntsa 53*, 220-223.

Gough, D. I., and M. R. Ingham (1983). Interpretation methods for magnetometer arrays, *Rev. Geophys. Space Phys. 21*, 805-827.

Graves, J. (1873). On Earth currents, *J. Telegr. Eng. 2*, 102-123.

Green, A. R. (1977). The evolution of the Earth's crust and sedimentary basin development, in *The Earth's Crust*, J. G. Heacock, ed., Geophysical Monograph 20, Am. Geophysical Union, Washington, pp. 1-17.

Greener, J. G., and D. M. Schlapp (1979). A study of day-to-day variability of Sq over Europe, *J. Atmos. Terr. Phys. 41*, 217-223.

Gregori, G. P., and L. J. Lanzerotti (1979a). Geomagnetic depth sounding by means of oceanographic and aeromagnetic surveys, *Proc. IEEE 67*, 1029-1034.

Gregori, G. P., and L. J. Lanzerotti (1979b). The effect of coast lines on geomagnetic measurements—a commentary, *Riv. Ital. Geofis. Sci. Affini. 5*, 81-86.

Gregori, G. P., and L. J. Lanzerotti (1980). Geomagnetic depth sounding by induction arrow representation: A review, *Rev. Geophys. Space Phys. 18*, 203-209.

Gregori, G. P., and L. J. Lanzerotti (1982). The electrical conductivity structure in the lower crust *Geophys. Surv.*, 467-499.

Hansteen, C. (1860). The great auroral expedition of August 28, to September 4, 1859, 4th article, Observations at Christiania, *Am. J. Sci. Arts 29*, 386-399.

Harang, L. (1951). *The Aurorae*, Chapman and Hall, Ltd., London, 163 pp.

Hermance, J. F. (1983). Electromagnetic induction studies, *Rev. Geophys. Space Phys. 21*, 652-665.

Hessler, V. P. (1974). Causes, recording techniques, and characteristics of telluric currents, *Corrosion 56*, 1-18.

Hewson-Browne, R. C. (1981). The numerical solution of oceanic electromagnetic induction problems, *Geophys. J. R. Astron. Soc. 67*, 235-238.

Hewson-Browne, R. C., and P. C. Kendall (1981). Electromagnetic induction in the Earth in electrical contact with the oceans, *Geophys. J. R. Astron. Soc. 66*, 333-343.

Hobbs, B. A., and A. M. M. Brignall (1976). A method for solving general problems of electromagnetic induction in the oceans, *Geophys. J. R. Astron. Soc. 45*, 527-542.

Hobbs, B. A., and G. J. K. Dawes (1980). The effect of a simple model of the Pacific ocean on Sq variations, *J. Geomagn. Geoelectr. 32*, Suppl. I, SI59-SI66

Hohmann, G. W. (1983). Three-dimensional EM modeling, *Geophys. Surv. 6*, 27-53.

Honkura, Y. (1974). Electrical conductivity anomalies beneath the Japan Arc, *J. Geomagn. Geoelectr. 26*, 147-171.

Honkura, Y. (1981). Electric and magnetic approach to earthquake prediction, in *Current Research in Earthquake Prediction*, T. Rikitake, ed., pp. 301-383.

Honkura, Y., N. Isezaki, and K. Yaskawa (1981). Electrical conductivity structure beneath the northwestern Philippine sea as inferred from the island effect on Mimami-Daito island, *J. Geomagn. Geoelectr. 33*, 365-377.

Hutton, V. R. S. (1976). The electrical conductivity of the earth and planets, *Rep. Prog. Phys. 39*, 487-572.

Jones, A. G. (1983). The problem of current channeling: A critical review, *Geophys. Surv. 6*, 79-122.

Jones, F. W., and A. M. Kelly (1966). Man-made telluric micropulsations, *Can. J. Phys. 44*, 3025-3031.

Kalmijn, A. J. (1978). Electric and magnetic sensory world of sharks, skates and rays, in *Sensory Biology of Sharks: Skates and Rays*, H. S. Hodgson and R. F. Matthewson, eds., U.S. Government Printing Office, Washington, D.C.

Keller, G. V. (1966). Electrical properties of rocks and minerals, in *Handbook of Physical Constants*, S. P. Clark, Jr., ed., Memoir 97, Geological Society of America, Boulder, Colo., pp. 553-557.

Keller, G. V. (1976). Foreword, *IEEE Trans. Geosci. Electron. GE-14*, 218-220.

Kendall, P. C., and D. A. Quinney (1983). Induction in the oceans, *Geophys. J. R. Astron. Soc 74*, 239-255.

Kirkwood, S. C., V. R. S. Hutton, and J. Sik (1981). A geomagnetic study of the Great Glen Fault, *Geophys. J. R. Astron. Soc. 66*, 481-490.

Klein, M., P. Louvet, and P. Morat (1975). Measurement of electromagnetic effects generated by swell, *Phys. Earth Planet. Inter. 10*, 49-54.

Kovalevskiy, I. V., N. V. Mikerina, V. V. Novysh, and O. P. Gorodnicheva (1961). Distribution of the Earth currents from an electrified railroad in the Southern Urals, *Geomagn. Aeron. 1*, 723-726.

Kurtz, R. D., E. R. Niblett, M. Chouteau, W. J. Scott, and L. R. Newitt (1981). An anomalous electrical resistivity zone near Ste-Mathilde, Quebec, Contr. 922, Earth Phys. Branch, Department of Energy, Mines, and Resources, Ottawa, pp. 56-67.

La Cour, D., and E. Hoge (1937). Note on the effects of electrification of railways passing in the area of the Copenhagen Observatory, *Bull. Int. Assoc. Terr. Magn. Atmos. Electr. 10*, 302-306.

Langel, R. A. (1982). Results from the MAGSAT mission, *Johns Hopkins APL Tech. Dig. 3*, 307-324.

Lanzerotti, L. J. (1979a). Impacts of ionospheric/magnetospheric processes on terrestrial science and technology, in *Solar System Plasma Physics* (3), L. J. Lanzerotti, C. F. Kennel, and E. N. Parker, eds., North-Holland, Amsterdam, pp. 317-363.

Lanzerotti, L. J. (1979b). Geomagnetic influences on man-made systems, *J. Atmos. Terr. Phys. 41*, 787-796.

Lanzerotti, L. J. (1979c). Geomagnetic disturbances and technological systems, *National Comm. Confer.* (Nov.), 7.1.1-7.1.4.

Lanzerotti, L. J. (1983). Geomagnetic induction effects in ground-based systems, *Space Sci. Rev. 34*, 347-356.

Lanzerotti, L. J., C. G. Maclennan, and C. Evans (1977). Magnetic fluctuations and ionosphere conductivity changes measured at Siple Station, *Antarct. J. 12*, 186-189.

Larkin, R. P., and P. J. Sutherland (1977). Migrating birds respond to Project Seafarer's electromagnetic field, *Science*, 777-779.

Larsen, J. C., and T. B. Sanford (1985). Florida current volume transports from voltage measurements, *Science 227*, 302-304.

Law, L. K. (1983). Marine electromagnetic research, *Geophys. Surv. 6*, 123-135.

Leggett, W. C. (1977). The ecology of fish migration, *Ann. Rev. Ecol. Syst. 8*.

Le Mouël, J. L., and M. Menvielle (1982). Geomagnetic variation anomalies and deflection of telluric currents, *Geophys. J. R. Astron. Soc. 68*, 575-587.

Liboff, A. R., T. Williams, Jr., D. M. Strong, and R. Wistar, Jr. (1984). Time-varying magnetic fields: Effect on DNA synthesis, *Science 223*, 818-820.

Lilley, F. E. M., and D. V. Woods (1978). The channeling of natural electric currents by orebodies, *Bull. Austr. Soc. Explor. Geophys. 9*, 62-63.

Lowes, F. J. (1982). On magnetic observations of electric trains, *Observatory 102*(1047), 44.

Malin, S. R. C. (1970). Separation of lunar daily geomagnetic variations into parts of ionospheric and oceanic origin, *Geophys. J. R. Astron. Soc. 21*, 447-455.

Malin, S. R. C. (1973). World-wide distribution of geomagnetic tides, *Phil. Trans. R. Soc. London 274A*, 551-593.

Matsushita, S. (1967). Solar quiet and lunar daily variation fields, in *Physics of Geomagnetic Phenomena*, S. Matsushita and W. H. Campbell, eds., Academic Press, New York, pp. 301-424.

Matsushita, S., and H. Maeda (1965a). On the geomagnetic solar quiet daily variation field during the IGY, *J. Geophys. Res. 70.*, 2535-2558.

Matsushita, S., and H. Maeda (1965b). On the geomagnetic lunar daily variation field, *J. Geophys. Res. 70*, 2559-2578.

Maxwell, J. C. (1984). What is the lithosphere? *EOS 65*(17), 321-325.

McKinnon, J. (1972). The August 1972 solar activity and related geophysical effects, NOAA Space Environment Laboratory Report, December.

Meloni, A., L. J. Lanzerotti, and G. P. Gregori (1983). Induction of currents in long submarine cables by natural phenomena, *Rev. Geophys. Space Phys. 21*, 795-803.

Meunier, J. (1969). Sondage électrique de le croûte utilisant des courants de retour industriels, *C. R. Acad. Sci. Ser. B 268*, 514-517.

Mikerina, N. V. (1962). The study of interference at the Voyeykovo magnetic observatory, *Geomagn. Aeron. 2*, 941-944.

Miller, S. L. (1974). The nature and occurrence of clathrate hydrates, in *Natural Gases in Marine Sediments*, I. R. Kaplan, ed., Plenum Press, New York, pp. 151-177.

Miyakoshi, J. (1980). Electrical conductivity structure beneath the Japan island arc by geomagnetic induction study, *Adv. Earth Planet. Sci. 8*, 153-161.

Moore, F. R. (1977). Geomagnetic disturbance and the orientation of nocturnally migrating birds, *Science 196*, 682-684.

Moureaux, T. H. (1896). L'installation d'une station d'étude des courants telluriques a l'Observatoire du Parc Saint Maur, *Soc. Met. France Ann. 4*, 25-38.

Nienaber, W., R. D. Hibbs, H. W. Dosso, and L. K. Law (1982). An estimate of the conductivity structure for the Vancouver Island region from geomagnetic results, *Phys. Earth Planet. Inter. 27*, 300-305.

Oxburgh, E. R. (1981). Heat flow and differences in lithosphere thickness, *Phil. Trans. R. Soc. London A301*, 337-346.

Parker, R. L. (1983). The magnetotelluric inverse problem, *Geophys. Surv. 6*, 5-25.

Parkinson, W. D. (1975). The computation of electric currents induced in the oceans, *J. Geomagn. Geoelectr. 27*, 33-46.

Parkinson, W. D. (1982). *Introduction to Geomagnetism*, Elsevier, Amsterdam, 433 pp.

Parkinson, W. D., and F. W. Jones (1979). The geomagnetic coast effect, *Rev. Geophys. Space Phys. 17*, 1999-2015.

Patra, H. P., and K. Mallick (1980). Geosounding principles, 2, in *Time Varying Geoelectric Soundings*, Elsevier, Amsterdam, pp. 1-419.

Paulikas, G. A., and L. J. Lanzerotti (1982). Impact of geospace on terrestrial technology, *Astronaut. Aeronaut.*, 42-47.

Peabody, A. W. (1979). Considerations of telluric current effects on pipelines, in *Solar System Plasma Physics*, L. J. Lanzerotti, C. F. Kennel, and E. N. Parker, eds., North-Holland, Amsterdam, pp. 349-352.

Peckover, R. S. (1973). Oceanic electric currents induced by fluid convection, *Phys. Earth Planet. Inter. 7*, 137-142.

Pirjola, R. (1983). Induction in power transmission lines during geomagnetic disturbances, *Space Sci. Rev. 85*, 185-193.

Porstendorfer, G. (1976). Electromagnetic field components and magnetotelluric sounding curves above horizontally inhomogeneous or anisotropic model media (catalogue of models), in *Geoelectric and Geothermal Studies (East-Central Europe, Soviet Asia), KAPG Monograph*, A. Adam, ed., Akademiai Kiado, Budapest, pp. 152-164.

Prandle, D. (1978). Monthly-mean residual flows through the Dover straits, 1949-1972, *J. Mar. Biol. Assoc. U.K. 58*, 965-973.

Prandle, D. (1979). Recordings of potential difference across the Port Patrick-Donaghadee submarine cable (1977/78), *Rep. Inst. Oceanog. Sci. Bidston Obs. 83*.

Prandle, D., and A. J. Harrison (1975). Recordings of the potential difference across the Port Patrick-Donaghedee submarine cable, *Rep. Inst. Oceanog. Sci. Bidston Obs. 21*.

Prescott, G. B. (1860). The great auroral exhibition of August 28 to September 4, 1859 (2nd article), *Am. J. Sci. Arts 29*, II ser. (85), 92-95.

Prescott, G. B. (1866). *History, Theory and Practice of the Electric Telegraph*, IV ed., Ticknor and Fields, Boston.

Price, A. J. (1967). Electromagnetic induction within the earth, in *Physics of Geomagnetic Phenomena 1*, S. Matsushita, and W. H. Campbell, eds., Academic Press, New York, pp. 235-298.

Reford, M. S. (1979). Problems of magnetic fluctuations in geophysical exploration, in *Solar System Plasma Physics*, L. J. Lanzerotti, C. F. Kennel, and E. N. Parker, eds., North-Holland, Amsterdam, pp. 356-360.

Reiff, P. H. (1983). Polar and auroral phenomena, *Rev. Geophys. Space Phys. 21*, 418-433.

Riddihough, R. P. (1969). A geographical pattern of daily magnetic variation over Northwest Europe, *Ann. Geophys. 25*, 739-745.

Rikitake, T. (1966). *Electromagnetic Induction and the Earth's Interior*, Elsevier, Amsterdam, 308 pp.

Rokityansky, I. I. (1982). *Geoelectromagnetic Investigation of the Earth's Crust and Mantle*, Springer-Verlag, Berlin, 381 pp.

Root, H. G. (1979). Earth-current effects on communication-cable power subsystems, *IEEE Trans. Electromagn. Compat. EMC-21*, 87-922.

Rössiger, M. (1942). Die Entstörung magnetischer Beobachtungsräume und erdmagnetischer Observatorium von Gleichstrom-Magnetfeldern der elektrischen Bahnen, *Naturwissenschaften 50/51*, 753-755.

Salvage, B. (1975). Overhead lines or underground cables: The problem of electrical power transmission, *Endeavour 34*, 3-8.

Sanders, R. (1961). Effect of terrestrial electromagnetic storms on wireless communications, *IRE Trans. Commun. Syst.* (December), 367-377.

Sato, T. (1965). Long-period geomagnetic oscillations in southern high latitudes, in *Geomagnetism and Aeronomy*, A. H. Waynick, ed., American Geophys. Union, Washington, D.C., pp. 173-188.

Saunders, H. (1880). Earth-currents, *Electrician 167* (August 21).

Saunders, H. C. (1881). Discussion of the paper by A. J. S. Adams "Earth Currents" (2nd paper), *J. Soc. Telegr. Eng. Electricians 10*, 46-48.

Schelleng, J. C. (1930). Some problems in short-wave telephone transmission, *Proc. IRE 18*, 913-938.

Schlapp, D. M. (1968). World-wide morphology of day-to-day variability of Sq, *J. Atmos. Terr. Phys. 30*, 1761-1776.

Schmucker, U. (1970). Anomalies of geomagnetic variations in the Southwestern United States, *Bull. Scripps Inst. Oceanog. 13*, 1-165.

Sebesta, D. (1979). Impact of magnetic storms probed, *Electr. World* (March 1), 52-53.

Semevskiy, R. B., K. G. Stavrov, and B. N. Demin (1978). Possibilities of investigating the magnetic fields of ocean waves by towed magnetometers, *Geomagn. Aeron. 18*, 345-347.

Sik, J. M., V. R. S. Hutton, G. J. K. Dawes, and S. C. Kirkwood (1981). A geomagnetic variation study of Scotland, *Geophys. J. R. Astron. Soc. 66*, 491-512.

Soller, D. R., R. D. Day, and R. D. Brown (1982). A new global crustal thickness map, *Tectonics 1*, 125-149.

Southwood, D. J., and W. J. Hughes (1978). Source induced vertical components in geomagnetic pulsation signals, *Planet. Space Sci. 26*, 715-720.

Srivastava, B. J. (1981). Geomagnetic results from Sabhawalla, Yangi-Bazar and Alma-Ata in relation to the asthenosphere beneath the Pamir-Himalaya, *Phys. Earth Planet. Inter. 25*, 210-218.

Srivastava, B. J., and H. Abbas (1980). An interpretation of the induction arrows at Indian stations, *J. Geomagn. Geoelectr. 32* (Suppl. II), SI187-SI196.

Störmer, C. (1955). *The Polar Aurora*, Clarendon Press, Oxford, 403 pp.

Summers, D. M. (1982). On the frequency response of induction anomalies, *Geophys. J. R. Astron. Soc. 70*, 487-503.

Thakur, N. K., M. V. Mahashabde, B. R. Arora, and B. P. Singh (1981). Anomalies in geomagnetic variations on peninsular India near Palk Straight, *Geophys. Res. Lett. 8*, 947-950.

Thomson, K. S. (1983). The sense of discovery and vice-versa, *Am. Sci. 71*, 522-524.

Tsikerman, L. Ya. (1960). Insulation of buried metal pipes to prevent corrosion, Gosstroiizdat, Moscow.

U.S. Geodynamics Committee (1983). *The Lithosphere—Report of a Workshop*, National Academy Press, Washington, D.C., 84 pp.

Varentsov, I. M. (1983). Modern trends in the solution of forward and inverse 3D electromagnetic induction problems, *Geophys. Surv. 6*, 55-78.

Varley, C. F. (1873). Discussion of a few papers on Earth currents, *J. Soc. Telegr. Eng. 2*, 111-114.

Walker, M. M., J. L. Kirschvink, S.-B. R. Chang, and A. E. Dizon (1984). A candidate magnetic sense organ in the yellowfin tuna, *Thunnus albacares*, *Science 224*, 751-753.

Ward, S. H. (1983). Controlled source electrical methods for deep exploration, *Geophys. Surv. 6*, 137-152.

Wertheim, G. K. (1954). Studies of electrical potential between Key West, Florida, and Havana, Cuba, *Trans. AGU 35*, 872.

Williams, D. J. (1979). Magnetosphere impacts on ground-based power systems, in *Solar System Plasma Physics*, L. J. Lanzerotti, C. F. Kennel, and E. N. Parker, eds., North-Holland, Amsterdam, pp. 327-330.

Winch, D. E. (1981). Spherical harmonic analysis of geomagnetic tides, 1964-1965, *Phil. Trans. R. Soc. London A303*, 1-104.

Winckler, J. R., L. Peterson, R. Hoffman, and R. Arnoldy (1959). Auroral x rays, cosmic rays, and related phenomena during the storm of February 10-11, 1958, *J. Geophys. Res. 64*, 597-610.

Wollaston, C. (1881). Discussion of the paper by A. J. S. Adams "Earth currents" (2nd paper), *J. Soc. Telegr. Eng. Electricians 10*, 50-51; 85-87.

Woods, D. V., and F. E. M. Lilley (1980). Anomalous geomagnetic variations and the concentration of telluric currents in south-west Queensland, Australia, *Geophys. J. R. Astron. Soc. 62*, 675-689.

Yanagihara, K. (1977). Magnetic field disturbance produced by electric railway, *Mem. Kakioka Magn. Obs.* (Suppl. 7), 17-35.

Yanagihara, K., and H. Oshima (1953). On the Earth-current disturbances at Haranomachi caused by the leakage current from the electric railway Fukushima-Yonezawa [in Japanese], *Mem. Kakioka Magn. Obs. 6*, 119-134.

Yanagihara, K., and T. Yokouchi (1965). Local anomaly of Earth-currents and Earth-resistivity [in Japanese], *Mem. Kakioka Magn. Obs. 12*, 105-113.

Yoshimatsu, T. (1964). Results of geomagnetic routine observations and earthquakes; locality of time changes of short period variations [in Japanese], *Mem. Kakioka Magn. Obs. 11*, 55-68.

APPENDIX: HISTORICAL DEVELOPMENT

A selective sketch of the historical development of the understanding of telluric currents follows. It is essentially impossible for the present authors to attempt to give full justice to all authors of the most recent investigations. It is particularly difficult to evaluate these recent works in a historical context. For more extensive general aspects of the subject and for recent literature references, the interested reader should refer to Dosso and Weaver (1983). A recent excellent review of primarily American work is contained in Hermance (1983), while Rokityansky (1982) and Berdichevsky and Zhdanov (1984) contain many references to Eastern literature.

1540 First reported measurement of geomagnetic declination and dip in London (as discussed, for example, in Malin and Bullard, 1981; Barraclough, 1982). For the early history of geomagnetism, including the works of Gilbert and Gauss, refer also to Mitchell (1932a, 1932b; 1937), Chapman (1963), Mattis (1965, Chap. 1), Parkinson (1982, Chap. 6), and Merrill and McElhinny (1983).

1600 First modeling of the geomagnetic field by Gilbert's (1600) terrella (Malin, 1983).

1821 Davy (1821) suggested the existence of Earth currents that, he argued, could be responsible for variations in the geomagnetic declination (Burbank, 1905).

1832 Faraday (1832) envisaged for the first time the existence of induced currents in water, related to water flows and tides. He also attempted, without success, to detect, from the Waterloo Bridge, such currents flowing within the Thames. Gauss (1833) reported the first measurements, on May 21, 1832, of the absolute value of the geomagnetic field (Malin, 1982).

1846-1847 Barlow (1849) made the first observations, in England, "on the spontaneous electric currents observed in the wires of the electric telegraph."

1848 Matteucci detected induced currents in the telegraph wire between Florence and Pisa, while Highton observed the same effect in England (see section on Communication Cables).

1850 Similar effects were reported in the United States.

1859 A telegraph line in the United States was reported operated by means of the natural induced currents during geomagnetic disturbances on September 2.

1862 Lamont (1862) reported one of the first experiments to specifically address Earth currents (carried out in the Munich Alps).

1865 Experiment by Airy (1868) on two wires of 13 and 16 km from Greenwich.

1867 Secchi (1867) reported measurements on two almost orthogonal telegraph lines of lengths 58 km (Rome-Arsoli) and 52 km (Rome-Anzio).

1881 The Electrical Congress, meeting in Paris, recommended that certain short lines be set apart in each country for the study of Earth current phenomena and that longer lines be used as frequently as possible (Burbank, 1905).

1884-1887 Four complete years of records on two telegraph wires in Germany (262 and 120 km) investigated by Weinstein (1902) and Steiner (1908).

1883-1884 Blavier (1884) recorded, for 9 months, Earth potentials on five long telegraph lines extending from Paris, ranging in length from 200 to 390 km. See also Counil *et al.* (1983).

1886 Shyda (1886) reported an Earth current study on the land line plus ocean cable route from Nagasaki, Japan, to Fusan, Korea.

1889 Schuster (1883, 1908) performed the first investigations on the diurnal variation of the geomagnetic field. He concluded that the origin is external, that the Earth must have an upper layer less conducting than that deep in the interior, and he proposed the "suggestive cause" of tidal motion in the atmosphere for the origin of the observed diurnal variation.

1892-1985 Two orthogonal Earth current lines, ~15 km each, were established at Saint-Maur-des-Fossés Observatory southwest of Paris (Moureaux, 1895, 1896; Bossler, 1912; Rougerie, 1940; Counil *et al.*, 1983).

1893 Moureaux (1893) found that the east-west Earth currents in the Paris basin were "exactly" correlated with the H-component of the geomagnetic field (i.e., the horizontal, north-south component), while this did not appear to be true for the north-south Earth current and the declination (east-west horizontal) geomagnetic field. This was the first reported detection of what is now interpreted in terms of telluric currents channeled east-west in the Seine basin from the Atlantic Ocean.

1905 Burbank (1905) provided a comprehensive bibliography on Earth currents.

1908 Van Bemmelen (1908) found that geomagnetic storm sudden commencements (ssc's) have opposite signs at Kew (close to London) and at St. Maur (close to Paris). He correctly explained this in terms of electric currents flowing in the English Channel.

1909 Schmidt (1909) investigated geomagnetic storms at Potsdam and at the Hilf Observatory (13 km south of Potsdam).

1912-1913 Van Bemmelen (1912, 1913) investigated the lunar period magnetic variation at 15 observatories.

1917-1918 Terada (1917) and Dechévren (1918a, 1918b) investigated Earth currents in Japan and in England (Jersey), respectively.

1918 The British Admiralty succeeded for the first time to detect electro-magnetic disturbances related to sea-water flows (Young *et al.*, 1920; figure reported in Chapman and Bartels, 1940).

1919 Chapman (1919) performed a systematic (and still quite valuable) analysis on the diurnal magnetic variation at 21 observatories, based on records collected in 1905.

1922 Bauer (1922) reviewed the status of Earth current studies.

Some historical points of interest in the past 60 years include the following:

1923 Chapman and Whitehead (1923) appear to have been the first investigators to be concerned with induction effects associated with the auroral electrojet (a localized current system). They erroneously concluded that geomagnetic storm effects at low latitudes are produced by Earth currents induced by the auroral electrojet.

1927-1928 Baird (1927) and Skey (1928) detected for the first time (at Watheroo in Australia and at Amberley and Christchurch in New Zealand, respectively) the intersection of what is now called the Parkinson plane (see, e.g., Gregori and Lanzerotti, 1980) with the DZ plane (i.e., the vertical, east-west oriented plane).

1930 Chapman and Price (1930) reconsidered the Chapman and Whitehead (1923) analysis and clearly stated that "the storm-time variations of the geomagnetic field in low latitudes cannot be due to currents, induced either the Earth or in a conducting layer of the atmosphere, by varying primary currents in the auroral zones."

1931 Cooperative project between the U.S. Coast and Geodetic Survey, the Carnegie Institution of Washington, and the American Telephone and Telegraph Company initiated at Tucson magnetic observatory to study Earth currents.

1936 Bossolasco (1936) detected for the first time (from measurements performed at Mogadiscio, Somalia, during the second International Polar Year, 1932-33) what is now called the Parkinson plane.

1949 De Wet (1949) attempted a numerical computation of the induction effects in oceans taking into account the coastal shapes.

1950 Ashour (1950) estimated the decay time of induced telluric currents within oceans. Constantinescu (1950) discovered what is now called the Parkinson plane and draw a plot, which is quite similar to a Wiese plot (see, e.g., Gregori and Lanzerotti, 1980).

1953 Rikitake and Yokoyama (1953) clearly stated the existence of the Parkinson plane. Banno (1953) detected for the first time the coast effect on Earth currents at Memambetsu (Hokkaido).

1954 Fleischer (1954a, 1954b, 1954c) hypothesized an east-west electric conductor 70 to 100 km deep beneath Bremen. Kertz (1954) stated that it cannot be lower than 80 km. Bartels (1957) estimated a depth of 50 to 100 km. Schmucker (1959) estimated a cylinder 63 km in radius, 100 km deep. Porstendorfer (1966) estimated high conductivity (0.2-0.5 mho/m) down to 10 km depth, an insulator (0.0001 mho/m) down to 100 km, a conductor (0.1 mho/m) between 100 and 130 km, an insulator (0.0001 mho/m) between 130 and 400 km, and 0.1 mho/m underneath. Vozoff and Swift (1968) reported a sedimentary layer (1.0 mho/m) 6 km deep in North Germany (8 sites from Braunschweig to Luebeck). The North German conductivity anomaly is now believed to be principally produced by surface-hydrated sedimentary layers that channel electric currents from the North Sea eastward to Poland. This is a classic example of how difficult the inversion (interpretation) problem is for geomagnetic measurements.

1955 Rikitake and Yokoyama (1955) appear to be the first authors to use the term "coast effect." In theoretically calculating a model of electromagnetic induction in a hemispherical ocean, they noted an enhanced magnetic field close to the coasts.

1958 Mansurov (1958) used the term "coastal effect" in analyzing geomagnetic measurements made at Mirny Station, Antarctica.

1959 Parkinson (1959, 1962a, 1962b, 1964), in a series of classic papers, analyzed in detail what is now called the Parkinson plane for geomagnetic measurements.

APPENDIX REFERENCES

Airy, G. B. (1868). Comparison of magnetic disturbances recorded by self-registering magnetometers at the Royal Observatory, Greenwich, with magnetic disturbances described from the corresponding terrestrial galvanic currents recorded by the self-registering galvanometers of the Royal Observatory, *Phil. Trans. R. Soc. 158A*, 465-472.

Ashour, A. A. (1950). The induction of electric currents in a uniform circular disk, *Q. J. Mech. Appl. Math. 3*, 119-128.

Baird, H. F. (1927). A preliminary investigation of some features of four magnetic storms recorded at seven magnetic observatories in the Pacific Ocean region during 1924, Thesis, Univ. of New Zealand.

Banno, N. (1953). On the Earth-current potentials at the Memambetsu magnetic observatory [in Japanese], *Mem. Kakioka Magn. Obs. 6*, 114-118.

Barlow, W. H. (1849). On the spontaneous electrical currents observed in the wires of the electric telegraph, *Phil. Trans. R. Soc. 61A*, 61-72.

Barraclough, D. R. (1982). Historical observations of the geomagnetic field, *Phil. Trans. R. Soc. A306*, 71-78.

Bartels, J. (1957). Erdmagnetische Tiefen-sondierungen, *Geol. Rdsch. 46*, 99-101.

Bauer, L. A. (1922). Some results of recent Earth-current observations and relations with solar activity, terrestrial magnetism and atmospheric electricity, *Terr. Magn. Atmos. Electr. 27*, 1-30.

Berdichevsky, M. N., and M. S. Zhdanov (1984). *Advanced Theory of Deep Geomagnetic Sounding*, Elsevier, 408 pp.

Blavier, E. E. (1884). Sur les courants telluriques, *C. R. Hebd. Séanc Acad. Sci. 98*, 1043-1045.

Bossler, J. (1912). Sur les relations des orages magnétiques et des phénomènes solaries, Thèse de specialité, Paris.

Bossolasco, M. (1936). Sur la nature des perturbations magnétiques, *C. R. Hebd. Séanc. Acad. Sci. 203*, 676-678.

Burbank, J. E. (1905). Earth-currents and a proposed method for their investigation, *Terr. Magn. Atmos. Electr. 10*, 23-49.

Chapman, S. (1919). The solar and lunar diurnal variations of terrestrial magnetism, *Phil. Trans. R. Soc. A218*, 1-118.

Chapman, S. (1963). Solar plasma, geomagnetism and aurora, in *Geophysics, The Earth's Environment*, C. DeWitt, J. Hieblot, and A. Lebaeu, eds., Gordon and Breach, pp. 371-502.

Chapman, S., and J. Bartels (1940). *Geomagnetism* (2 volumes), Clarendon Press, Oxford, 1049 pp.

Chapman, S., and A. Price (1930). The electric and magnetic state of the interior of the Earth as inferred form terrestrial magnetic variations, *Phil. Trans. R. Soc. A229*, 427-460.

Chapman, S., and T. T. Whitehead (1923). The influence of electrically conducting material within the Earth on various phenomena of terrestrial magnetism, *Trans. Camb. Phil. Soc. 22*, 463-482.

Constantinescu, L. (1950). Sudden commencements of magnetic storms in the years 1944-1949 [In Rumanian], *Lucr. Ses. Gen. Stiint. Acad. Rep. Pop. Rom.*

Counil, J. L., J. L. LeMouel, and M. Menvielle (1983). A study of the diurnal variation of the electromagnetic field in northern France using ancient recordings, *Geophys. J. R. Astron. Soc. 78*, 831-845.

Davy, H. (1821). On magnetic phenomena produced by electricity, *Phil. Trans. R. Soc.*, 7-19.

Dechévren, M. (1918a). Results of observations of Earth-currents made at Jersey, England, 1916-1917 (abstract) *Terr. Magn. Atmos. Electr. 23*, 37-39.

Dechévren, M. (1918b). Additional results of Earth-current observations at Jersey, England, *Terr. Magn. Atmos. Electr. 23*, 145-147.

De Wet, J. M. (1949). Numerical methods of solving electromagnetic induction problems, with applications of the theory of electric currents induced in the oceans, Thesis, Univ. of London.

Dosso, H. W., and J. T. Weaver, eds. (1983). Electromagnetic induction in the Earth and Moon: Invited review papers presented at the 6th Induction Workshop, *Geophys. Surv. 6*, 1-216.

Faraday, M. (1832). Experimental researches in electricity, *Phil. Trans. R. Soc.*, 163-194.

Fleischer, U. (1954a). Charakteristische erdmagnetische Baystörungen in Mitteleuropa and ihr innerer Anteil, *Z. Geophys. 20*, 120-136.

Fleischer, U. (1954b). Ein Erdstrom in tieferen untergrund Norddeutschlands waerend erdmagnetischer Baystörungen, *Naturwissenschaften 41*, 114-115.

Fleischer, U. (1954c). Ein Erdstrom in tiefereu untergrund Norddentschlands und sein anteil in dem magnetischen Baysörungen, Diss. Göttigen.

Gauss, C. F. (1833). Intensity of the terrestrial magnetic force, reduced to absolute units [in Latin], Göttingen.

Gilbert, W. (1600). *De Magnete* [in Latin], P. Short, London, English translation—1900, Chiswick Press, London.

Gregori, G. P., and L. J. Lanzerotti (1980). Geomagnetic depth sounding by induction arrow representation: A review, *Rev. Geophys. Space. Phys. 18*, 203-209.

Hermance, J. F. (1983). Electromagnetic induction studies, *Rev. Geophys. Space Phys. 21*, 652-665.

Kertz, W. (1954). Modelle für erdmagnetsche induzierte elektrische störm ein Untergrund, *Nachr. Akad. Wiss. Göttingen, Math. Phys. Kl. 2A*, 101-110.

Lamont, J. V. (1862). Die Erdstrom und der zusammenhang Desselben mit dem Magnetismus der Erde, Leopold-Voss-Verlag, Leipzig und Muenchen.

Malin, S. R. C. (1982). Sesquicentenary of Gauss' first measurement of the absolute value of magnetic intensity, *Phil. Trans. R. Soc. A306*, 5-8.

Malin, S. R. C. (1983). Modelling the geomagnetic field, *Geophys. J. R. Astron. Soc. 74*, 147-157.

Malin, S. R. C., and E. Bullard (1981). The direction of the Earth's magnetic field at London, 1570-1975, *Phil. Trans. R. Soc. 299*, 357-423.

Mansurov, S. M. (1958). Causes of local geomagnetic variation in the Mirny region, *Inf. Byull. Sov. Antarkt. Eksped. 2*, 37-41, 1958; English translation, in *Sov. Antarctic Expedition, Inf. Bull. 1*, 82-85.

Mattis, D. C. (1965). *The Theory of Magnetism, An Introduction to the Study of Cooperative Phenomena*, Harper and Row, New York, pp. 1-303.

Merrill, R. T., and M. W. McElhinny (1983). *The Earth's Magnetic Field—Its History, Origin and Planetary Perspective*, Academic Press, 401 pp.

Mitchell, C. A. (1932a). On the directive property of a magnet in the Earth's field and the origin of the nautical compass, *Terr. Magn. Atmos. Electr. 37*, 105-146.

Mitchell, C. A. (1932b). The discovery of magnetic declination, *Terr. Magn. Atmos. Electr. 37*, 105-146.

Mitchell, C. A. (1937). The discovery of the magnetic inclination, *Terr. Magn. Atmos. Electr. 42*, 241-280.

Moureaux, Th. (1893). *Soc. Met. France, Annu. 1*, 825-828.

Moureaux, Th. (1895). Notice sur l'installation d'une station d'étude des courants telluriques, *Soc. Met. France, Annu. 3*.

Moureaux, Th. (1896). L'installation d'une station d'étude des courants telluriques a l'Observatoire du Parc Saint Maur, *Soc. Met. France, Annu. 4*, 25-38.

Parkinson, W. D. (1959). Direction of rapid geomagnetic fluctuations, *Geophys. J. R. Astron. Soc. 2*, 1-14.

Parkinson, W. D. (1962a). The influence of continents and oceans on geomagnetic variations, *Geophys. J. R. Astron. Soc. 6*, 441-449.

Parkinson, W. D. (1962b). Magnetic variations over the oceans, in *Geomagnetica* (publicacao comemorativa de 50-mo aniversario do Observatorio Magnetico de S. Mignel, Azores—Servico Meteorologico Nacional, Lisbona), 97-108.

Parkinson, W. D. (1964). Conductivity anomalies in Australia und the ocean effect, *J. Geomagn. Geoelectr. 15*, 222-226.

Parkinson, W. D. (1982). *Introduction to Geomagnetism*, Elsevier, 433 pp.

Porstendorfer, G. (1966). Die raumlische verteilung tellurischer Ströme mit Perioden von 30 Min in Mitteleuropa, *Bergakademie 8*, 461-463.

Rikitake, T., and I. Yokoyama (1953). Anomalous relations between H and Z components of transient geomagnetic variations, *J. Geomagn. Geoelectr. 5*, 59-65.

Rikitake, T., and I. Yokoyama (1955). *Bull. Earthquake Res. Inst.* (Tokyo Univ.) *33*, 297.

Rokityansky, I. I. (1982). *Geoelectromagnetic Investigation of the Earth's Crust and Mantle*, Springer-Verlag, Berlin, 381 pp.

Rougerie, P. (1940). Contribution a l'étude des courants telluriques, Thèse de specialité, Paris.

Schmidt, A. (1909). Die magnetische störung am 25 September 1909 zu Potsdam und Seddin, *Met. Z. 26*, 509-511.

Schmucker, H. (1959). Erdmagnetische Tiefensondierung in Deutschland 1957-1959. Magnetogramme und erste Auswertung, *Abh. Akad. Wiss. Göttingen (Beitr. IGJ) 5*, 1-51.

Schuster, A. (1883). The diurnal variation of terrestrial magnetism, *Phil. Trans. R. Soc. A180*, 467-518.

Schuster, A. (1908). The diurnal variation of terrestrial magnetism, *Phil. Trans. R. Soc. A208*, 163-204.

Secchi, P. (1867). Earth-currents on telegraph lines in Italy [in Italian], *C. R. Hebd. Séanc Acad. Sci. 58*, 1181.

Shyda, R. (1886). Earth-currents, *Trans. Seismol. Soc. Japan 9, Part I*.

Skey, H. F. (1928). Christchurch magnetic observatory—Report for the year 1926-27—Records of the survey of New Zealand 4, 42.

Steiner, L. (1908). On Earth-currents and magnetic variations, *Terr. Magn. Atmos. Elect. 13*, 57-62.

Terada, T. (1917). On rapid periodic variations of terrestrial magnetism, *J. Coll. Sci. Imp. Univ. Tokyo 37*, 56-84.

Van Bemmelen, W. (1908). The starting impulse of geomagnetic disturbances [in Dutch], *Versl. Gewone Vergad. Wis-en Natuurk, Afd. K. Akad. Wet.*, English edition, *Proc. Sec. Sci. K. Ned. Akad. Wet. 16*, 728-737.

Van Bemmelen, W. (1912). Die lunare variation des Erdmagnetismus, *Met. Z. 29*, 218-225.

Van Bemmelen, W. (1913). Berichtigung, *Met. Z. 30*, 589.

Vozoff, K., and C. M. Swift (1968). Magneto-telluric measurements in the North German basin, *Geophys. Prospect. 16*, 454-473.

Weinstein, B. (1902). Die Erdströme im Deutschen Reichstelegraphengebeit, und ihr Zusammenhamp mit den erdmagnetischen Erscheinungen, mit einen Atlas, Friedrich Vieweg und Shon, Braunschweig, 88 pages plus 19 plates, 1900. (A review by W. G. Cady is given in *Terr. Magn. Atmos. Electr. 7*, 149-152.

Young, F. B., H. Gerrard, and W. Jevons (1920). On electrical disturbances due to tides and waves, *Phil. Mag. 40*, 149-159.

III General Theory of Telluric Electric Wave Transmission and Reception

- (1) **Introduction**
  - (a) The reception and transmission of telluric electric waves employs methods and principles unlike those found in conventional electro-magnetic wave systems. Electric wave propagation within the interior of the earth is of a character much different than that propagation in the space exterior to the solid mass of the earth. The space within the mass of the earth is complicated by various degrees of magnetic permeability, dielectric permittivity, conductivity and resistivity, all these of various magnitudes for various directions. Further is the presence of significant static magnetic and static dielectric fields of induction.
  - (b) With conventional electro-magnetic structures the principles of wave reception are equivalent to the principles of wave transmission, this is known as the *law of reciprocity*. In part this law can be applied to the various sub-systems that form the telluric wave systems. However, certain antenna configurations depart from the reciprocity law in that the propagation factor for reception must lag in phase behind the electric wave to be received, where as the propagation factor for transmission must lead in phase ahead of the electric wave to be transmitted. This situation is analogous to the alternating current induction machine. For a given frequency in radians per sec. of electric excitation to the field of the induction machine the frequency in radians per second of rotation must fall behind the excitation frequency for the induction machine to receive energy as a motor. Conversely the frequency of rotation must push ahead of the excitation frequency for the induction machine to transmit energy as a generator. In this situation the angular frequency of excitation is of unit value or represents a relative condition of rest. The angular frequency of rotation has a relative negative or positive value, for positive or negative power flow respectively. For the antenna the situation is the same. The lagging velocity for receive and the leading velocity for transmit, this relative to the velocity of the electric wave in the medium of transmission or reception.
  - (c) An important condition for the transmission and reception of telluric electric waves is a single wire or uni-polar connection to the solid mass of the earth. Electro-magnetic transmission and reception requires a multi-polar or multiple wire connection, two wire being common. It is required for telluric wave operation that the antenna sub-system be self referencing, that is the antenna sub-system not grounding in the usual sense, since ground is now an active terminal. There can be no second wire since there is nothing to connect it to. Hence, the need for a single wire or uni-polar antenna characteristic.
  - (d) In the transmission and reception of telluric electric waves two departures exist with regard to the transmission and reception of electro-magnetic waves:

        - 1) The law of reciprocity is not applicable to the transfer of energy between the telluric wave and the antenna sub-system.
        - 2) The boundary condition or circuit law is not applicable to the connection of the antenna to the solid mass of the earth.
    - (e) Such electrical conditions, once common in early wireless development, have become largely unknown. Two principal systems emerged from this era having the proper characteristics for telluric electric wave applications:
        - 1) The oscillation transformer as developed by Nikola Tesla, 1900
        - 2) The multiple loaded aerial as developed by Ernst Alexanderson, 1919
- (2) **The Oscillation Transformer**
    - (a) The first development in the wireless transmission of electric waves was a telluric system based upon the application of an antenna sub-system known as the oscillation transformer. This transformer is a single winding coupled magnetically to an external resonant structure. Transformer operation resembles a constant current or ballast transformer. The single winding of the oscillation transformer resembles that of a simple reactance coil, however, only a single lead exists for communicating energy in and out of this coil structure. It is a single wire, uni-polar connection. The second lead of the coil is only connected to a small free space electro-static condenser.
    - (b) In the operation of the oscillation transformer the winding is not a simple reactance coil and magnetic field of induction. The dielectric field of induction now plays an important role, as energy now resides in the dielectric field in addition to energy residing in the magnetic field. In oscillation transformer operation the total energy divides evenly between the magnetic field and dielectric field of induction. The superposition of these two fields of induction give rise to complex electric waves. The oscillation transformer winding, thus operates as a wave guide structure, giving rise to electric waves through the exchange of magnetic and dielectric energy.
    - (c) Complex electric waves exist on the oscillation transformer winding during its resonant exchange of energy between the two fields. These standing waves produce a phase displacement in *time* cycle of energy exchange and in *length* along the winding structure. The displacements exist as a hysteresis cycle, displacing the cause-effect relationship. This results in the transformer winding operating as a uni-polar system.
    - (d) The resonant structure coupled to the oscillation transformer winding is a simple magnetic reactance coil in a resonant relation with a simple electrostatic condenser. This circuit is proportioned to have minimal dissipative losses, that is it has a large magnification factor. This circuit provides the two wire connection for the supply or abstraction of energy to or from the oscillation transformer winding and its uni-polar connection to the earth.

- (e) In conjunction with the coupled resonant circuit the oscillation transformer winding serves as a phase transformer. This phase transformation provides the basis conversion from a multi-phase to a uni-phase connection. This phase transformation provides the basis conversion from a multi-phase to a uni-phase connection. This provides the single wire connection for the telluric electrical waves, transforming this to the multiple wire connection to a network sub-system.
- (f) The complex electric wave produced by the resonant electric fields of the oscillation transformer winding is analogous to those electric waves, which exist within the interior of the earth. This complex electric wave in the winding is the resultant of the superposition of transverse electric waves of a specific velocity and of longitudinal waves of a specific counter-velocity. This pair of electric waves propagate within the electric field of the winding. This winding can be proportioned to be attuned to the complex electric wave propagation within the interior of the earth. The winding becomes an analog of the specific telluric waves to be transmitted or received.
- (g) The transient impulses produced by the oscillation transformer are of analogous form to the transient impulses resulting from telluric wave propagation within the earth. In this manner the oscillation transformer responds as does the network sub-system previously described. The high and low pass functions are a direct result of transformer actions. Hereby the oscillation transformer serves as the network sub-system in addition to serving as the antenna sub-system. Thus the oscillation transformer in itself serves as a system for the transmission and reception of telluric electric waves.
- (h) The principal drawback in the application of the oscillation transformer to telluric waves is the inability to respond to a wide range of signal frequencies. Also is the lack of directivity in the spatial distribution of its response. Thus in the application of the oscillation transformer to telluric waves it can be proportioned to respond only to telluric waves of a single frequency and its related harmonic structure, that is to one specific transient electric wave form. Transformer response is to telluric waves from all directions, it having no directional character. This limits the use of the oscillation transformer to specific communication or broadcast functions and thus prohibits its use for broadband or generalized transmission or reception functions.

- (3) **The Multiple Loaded Aerial**
  - (a) Following the development of the oscillation transformer was its application to the system of wireless trammission developed by Guglielmo Marconi (1910). During its development by Nikola Tesla the wave guide and uni-polar properties of the oscillation transformer were not fully understood. Tesla repeatedly attempted to force the winding to operate as a simple magnetic reactance coil. The importance of the dielectric field of the winding and its complex relation to the magnetic field were to be missed by Tesla and his contemporaries. This situation would be further compounded by the efforts of Marconi.

- (b) The application of the oscillation transformer to the transmission and reception of telluric waves was under patent protection by Nikola Tesla. For Marconi to proceed with his wireless development, significant alterations had to be made. In the telluric wave system of Nikola Tesla the oscillation transformer alone served as the basic system for the transmission or reception of electric waves. Marconi would make important changes to the Tesla system in order to secure a wireless patent of his own. The basic modification was the extreme enlargement of the electro-static capacity of the free terminal of the oscillation transformer winding. An aerial-ground structure known as the Marconi "Flat Top", of considerable extent, was connected as a basic condenser to the oscillation transformer winding. The electro-static capacity of this aerial-ground structure greatly exceeded that of the oscillation transformer winding. Hereby the function of the oscillation transformer was reduced to that of a basic magnetic reactance coil. Now unable to resonate with the winding dielectric field, the winding lost the ability to operate as a phase transformer. It now operates as a di-polar or two wire system.

- (c) The aerial portion of the Marconi Flat Top was positioned over a similar structure in the ground. The length of this aerial-ground system several times larger than the width, this forming a large strip-line transmission structure. Thus the aerial-ground structure is a electrically short section of electro-magnetic transmission line. Within the electro-magnetic field of this section of line, a very large reactive power flow exists, this in an oscillitory energy exchange with the transformer. The coil and aerial-ground structure reduce to a basic resonant circuit. The power flow in this circuit contributes little to the ability of the Flat Top to transmit or receive electric waves. The Flat Top derives its ability to transmit or receive principally from it external dielectric field of induction. The lag of phase along the length of the Flat Top produces a small portion of external electro-magnetic activity and resulting waves. Hence, the Marconi Flat Top aerial-ground system is an ineffective structure for both electromagnetic and telluric electric waves.

- (d) The large reactive power flow within the confined portion of the Flat Top represents a useless or parasitic power flow. Its loading upon the oscillation transformer renders the winding a reactance coil. Therefore, the confined electro-magnetic field of induction inhibits the operation of this aerial-ground system in the transmission or reception of telluric electric waves.

- (e) While Marconi resorted to simple terminal impedance methods to minimize the effects of this reactive power flow, the basic situation remained unchanged. Ernst Alexanderson, while employed by the General Electric Company and the U.S. Navy (1919), developed a significant advancement in the Flat Top system. This development became the Alexanderson multiple loaded aerial. This aerial-ground system finds important applications to the transmission and reception of telluric electric waves.

- (f) The Alexanderson system is a direct adaption of the Marconi Flat Top. The basic external geometry is unchanged. However, the aerial and the ground elements of the strip-line configuration are sectionalized into a series of sub-section elements. Loading elements are inserted in the transitions between sub-section elements. The Alexanderson principle utilized this sequential loading to cancel or neutralize the reactive electro-magnetic power flow of the Flat Top system. The result is the aerial-ground system becomes a non electro-magnetic structure, with the dimensions of velocity and wavelength becoming undefined.

- (g) The Alexanderson system is no longer the simple strip-line of Marconi, but has become a complex system of alternate, sequential sections of transmission and loading structures. This configuration is analogous to a loaded long distance telephone line. The Alexanderson system has rendered the strip-line of Marconi a *wave-guide* type structure. The superposition of the magnetic field and the dielectric field in this wave-guide give rise to complex electric waves as with the oscillation transformer of Tesla. Hereby the Alexanderson system enables telluric wave transmission and reception.

- (h) The basic oscillation transformer winding exists in multiple with the Alexanderson system, each being connected at each of the sequential loading sections. These windings now operate unhampered by reactive power flow. Operation of these phase transformer windings in multiple allows for directional operation, unlike a single unit. In addition, in conjunction with the loading elements, the windings in multiple allows for a band pass characteristic to be established. Hereby the Alexanderson multiple loaded aerial-ground system overcomes the principal limitations of the oscillation transformer system of Tesla, the lack of directivity and bandwidth.

- (4) **Development of the Alexanderson System for the Propagation of Telluric Waves.**

  - (a) The basic Alexanderson system can be developed further for adaption to the propagation of telluric waves. Alexanderson would follow the path that Marconi followed from the Tesla system. The Alexanderson system was operated as a di-polar configuration for the propagation of electro-magnetic waves. This led to the extinction of the Alexanderson system as well as the systems from which it developed. Advancing the Alexanderson concept one step ahead, while retaining the original uni-polar concept of Tesla, results in an aerial-ground sub-system of perfect adaptability to the transmission and reception of telluric waves.

  - (b) In the layout of the Alexanderson system upon that of Marconi, the earthed portion of this system basically remained unchanged. This portion continued to operate as a single grounded conductor under the aerial portion of the system. No significant phase or potential differences exist along the continuous earthed portion of the Alexanderson system. Therefore, no electric waves can exist along this length of grounded conductor. This earthed portion of the aerial-ground system acts as a single ground electrode and can propagate telluric waves only in the manner of a single point source, as with the Tesla system. During the period of history during which the Alexanderson system existed, it was considered as a system for the propagation of electro-magnetic waves. This related to the vertical conductors rising from the grounded loading sections to the aerial structure above. The electric current related to this conductor gives rise to the propagation of electro-magnetic waves. However, the energy of these waves exists as a small portion of the total electric wave propagation of the Alexanderson aerial-ground system. Alexanderson as well as Marconi engineers understood that the Flat Top aerial and its adaptation by Alexanderson operated as an antenna for the propagation of *electro-static*, rather than electro-magnetic waves. Therefore, the Alexanderson aerial operates as a system for the transmission and reception of dielectric waves through its external dielectric field. Part of this dielectric field of induction is directed by the earthed ground structure into the interior of the earth. This induction gives rise to the propagation of telluric waves in a manner similar to that of Tesla.

- (c) The Alexanderson aerial-ground system is an advancement upon the Marconi system. The Marconi system is an adaptation of the Tesla oscillation transformer system. The antenna sub-system of the basic system for the propagation of telluric waves represents an advancement upon the system of Tesla, this lacking directivity and bandwidth and represents an advancement upon the system of Marconi/Alexanderson, which primarily propagated waves exterior to the mass of the earth. The advancement upon the Alexanderson system is the *elimination of the external propagation* of electric waves. Advancement centers upon the *earthed* portion of the aerial-ground system. Unlike the Alexanderson configuration loading is *divided in a balanced fashion* between both the aerial and earthed portions of the system. Hereby complex electric waves within the interior of the earth can be developed. The elements of the earthed portion of this system operate each independent of the other with no inter-connection. Each element consists of a vertical section projecting within the mass of the earth. The earthed portion of the aerial-ground structure exists as a sequential row of vertical earthed elements along the aerial axis. No longer is the earthed portion of the layout in the Flat Top configuration.

- (d) The aerial portion of the aerial-ground structure serves as a loaded section of transmission line, providing energy exchange to the individual loading sections and related earthed elements. This aerial configuration remains as with Alexanderson systems. However, the undivided ground portion of Marconi/Alexanderson design now exists as an aerial counterpoise above the loaded aerial portion of the antenna-ground system. Hence, the Flat Top has become inverted, with the ground portion above the aerial portion of the system. The upper Flat Top configuration serves to neutralize the electric wave propagation in the space external to the mass of the earth. This neutralizing aerial confines the electric wave propagation of the antenna sub-system to the interior of the earth. The actual Alexanderson aerial is reduced to a loaded transmission line, unbalanced with respect to an elevated ground plane. No external electric wave propagation exists.

- (e) A loaded transmission system is an analog system. Loading in its general form is a sequential series of alternate sections of real transmission line and of artificial transmission line. The artificial lines are analog equivalents of real propagation. Hereby the propagation on the aerial can be chosen at will through the interaction of real propagation with artificial (imaginary) propagation. The entire aerial becomes an analog network of real and imaginary parts, analogous to a complex wave propagation within the earth.

- (f) Development of the telluric wave antenna centers upon the control of the phase relation or lead-lag time element, along the row of vertical earthed elements. The reflection at the surface of the earth of standing and traveling telluric waves within produce specific images of phase displacement upon the surface of the earth. That is, the telluric waves develop specific points at the surface boundary. An analog of these waves is reproduced by the aerial portion of the antenna and connected with the earthed portion to facilitate the exchange of energy with the real wave through its projection upon the surface of the earth. The phase displacements of the individual earthed elements are now in mutual relation with the displacements of the telluric wave. The described antenna sub-system is attuned to the wave propagation within the interior of the earth.

- (5) **General Theory of Complex Electric Waves**
  - (a) Any electric wave is the product of the superposition of a magnetic field of induction and a dielectric field of induction. The pair of fields each represent the storage of electric energy within the structure of the field, magnetic or dielectric. Electric waves result from the exchange of electric energy between dielectric and magnetic fields of induction.The displacements of these inductions with respect of phase and distance determines the character of the resultant electric wave. Complex displacements give rise to complex electric waves.
  - (b) In common use are those electric waves that propagate along the axis of a system of two or more electric conductors. In this form of electric wave the magnetic and dielectric fields are both perpendicular to the axis of the system of electric conductors. The magnetic and dielectric fields are perpendicular to each other. Hence, the magnetic and dielectric fields of induction travel broadside or transverse to the propagation of the resultant electric wave along the electric conductors. The proportion of magnetic induction with respect to the portion of dielectric induction within an electric wave of this form is a numerical constant. This constant is numerically equivalent to the velocity of light in the space between the electric conductors. Also, it is a transverse electric wave, which propagates as a velocity, this velocity equivalent to the velocity of light in the space between the electric conductors. This common form of electric wave is called a transverse electro-magnetic wave (T.E.M.). The magnetic and dielectric fields are transverse to wave propagation.
  - (c) A complimentary electric wave exists in quadrature with the transverse electro-magnetic wave. Where the transverse wave propagates along the axis of the electric conductors, the quadrature wave propagates perpendicular to the axis of electric conductors. This conjugate electric wave is in space quadrature with the T.E.M. wave in any system of two or more electric conductors. As with the T.E.M. wave, this quadrature wave is the product of the

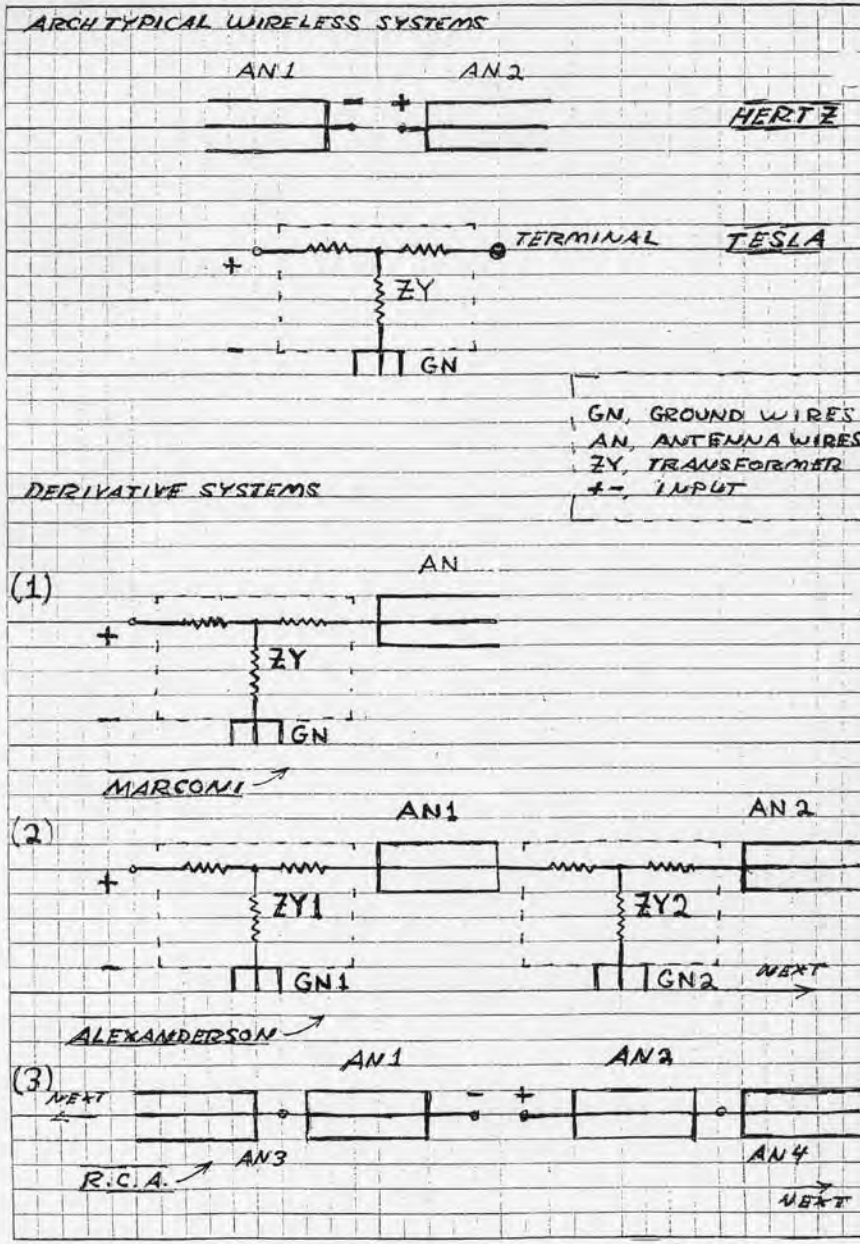
superposition of the magnetic and dielectric fields of induction. With the quadrature electric wave the pair of fields of induction are co-liner or longitudinal to the direction of electric wave propagation. Hence, the magnetic field, dielectric field and electric wave propagation are all in space quadrature with the axis of the system of electric conductors. This quadrature electric wave is called the longitudinal magnetic-dielectric wave (L.M.D.). The proportion of magnetic induction to the proportion of dielectric induction is not numerically equivalent to the velocity of light, nor is the dimension of propagation a velocity. That is, the longitudinal electric wave is not of the dimensions of unit length per unit time, as was the transverse electric wave. With the longitudinal electric wave the dimension of propagation is that of per unit length per unit time (per unit length-time). This propagation may be called a counter-velocity, representing propagation of electric waves through counter-space of per unit length.

- (d) In the general case of telluric electric waves, the transverse wave propagates from a point of origin to distant location through space of unit length over a period of unit time. The longitudinal wave propagates within the magnetic and dielectric fields themselves, within the point of origin, through a counterspace of per unit length over a period of per unit time. These two distinct forms of electric waves exist in a conjugate relation to each other. Hereby a complex electric wave propagates on a system of two or more electric conductors, with a real part, the T.E.M. wave and an image (imaginary) part, the L.M.D. wave. Their product is a complex quantity in the dimension of space. Thus the telluric electric wave is a complex electric wave consisting of a radiation component (T .E.M.) and a field of induction component (L.M.D.) in quadrature relation.

- (6) **Harmonic Structure of Transverse and Longitudinal Waveforms**
    - (a) In the propagation of transverse electro-magnetic waves a progressive phase lag or delay results as the wave propagates outward from its origin, along the propagating structure. This results in an increasing phase shift or time lag for increasing frequency of energy exchange. For finite, resonant systems of electric conductors this phase lag is in unit integral multiples of quarter cycle delays. These delay factors result in harmonics of the cycle of energy exchange within the system of electric conductors. For example, Fo, 3Fo, 5Fo, etc. as this harmonic series progresses each harmonic becomes progressive diminished in amplitude. For example, Ao, l/3 Ao, l/5 Ao, etc.
    - (b) The harmonic series is contrary for the condition of longitudinal magneto-dielectric waves. In this case a progressive phase lead is produced as the wave propagates inward from its origin, within the propagating structure. This results in an increasing phase shift or time lag for decreasing frequency of energy exchange. For finite, resonate systems of electric conductors the phase shift is in unit differential divisions of quarter cycle advances. These advance factors result in the production of harmonics of the cycle of energy exchange. These harmonics exist as a series of divisions upon the fundamental frequency of energy exchange. For example, Fo, 1/3 Fo, 1/5 Fo, etc. As this harmonic series progresses

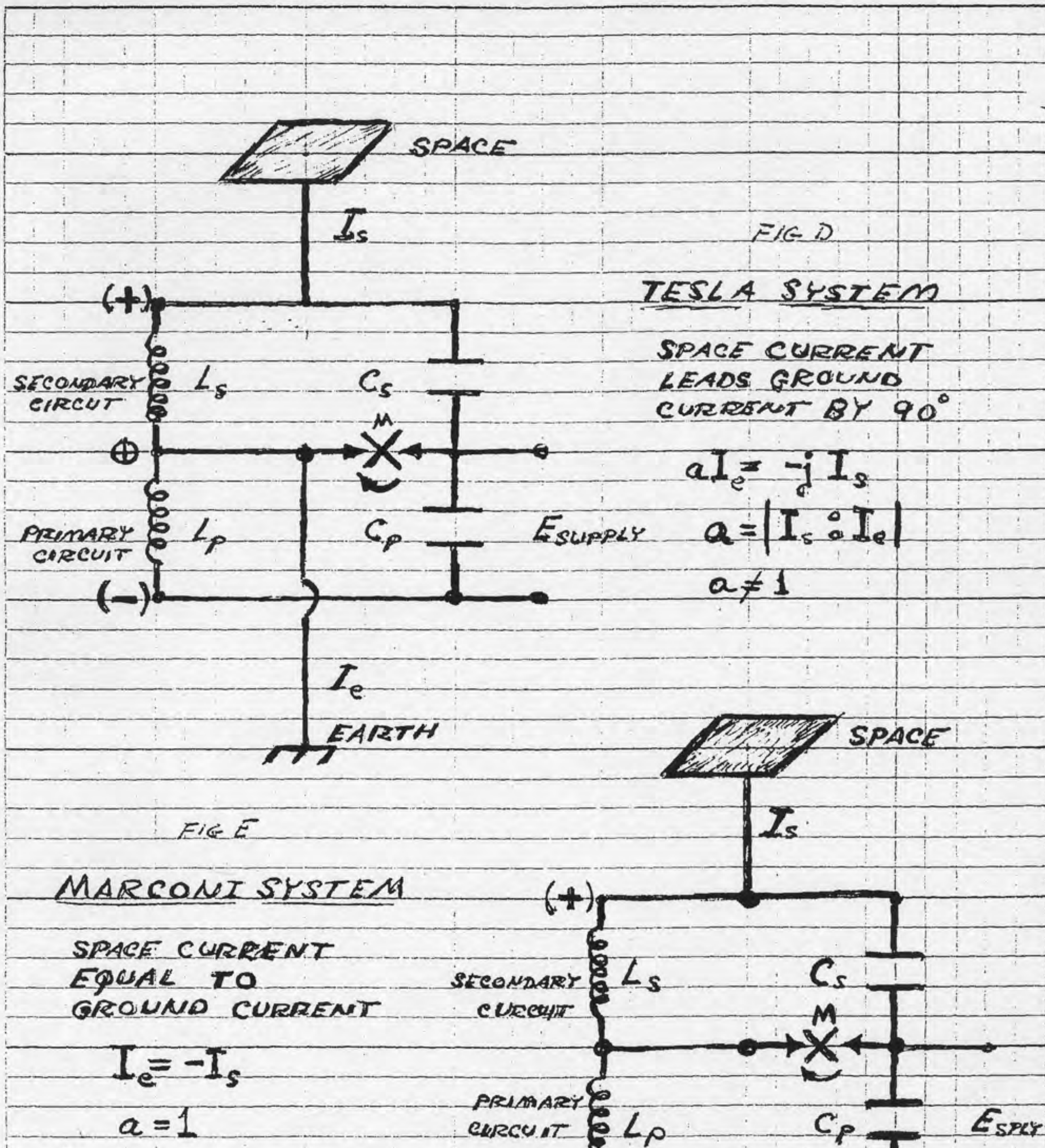
the amplitude of each harmonic is progressively diminished as with the T.E.M. wave. For example, Ao, l/3 Ao, l/5 Ao, etc.

- (c) The generalized, complex electric wave is the superposition of the time periods of T.E.M. propagation and its conjugate, the time periods of L.M.D. propagation. The resultant electric wave is a complex quantity in the domain of time as well as the domain of space. Where in the space domain it is unit length for T.E.M. and per unit length for L.M.D., it is in the time domain unit time for the T.E.M. and per unit time for the L.M.D. with respect to harmonic production. The complex electric wave is the product of a progressive harmonic series and of a degressive harmonic series. Hereby the wave structure can be proportioned to produce a variety of electrical transient impulses with respect to time as well as space.

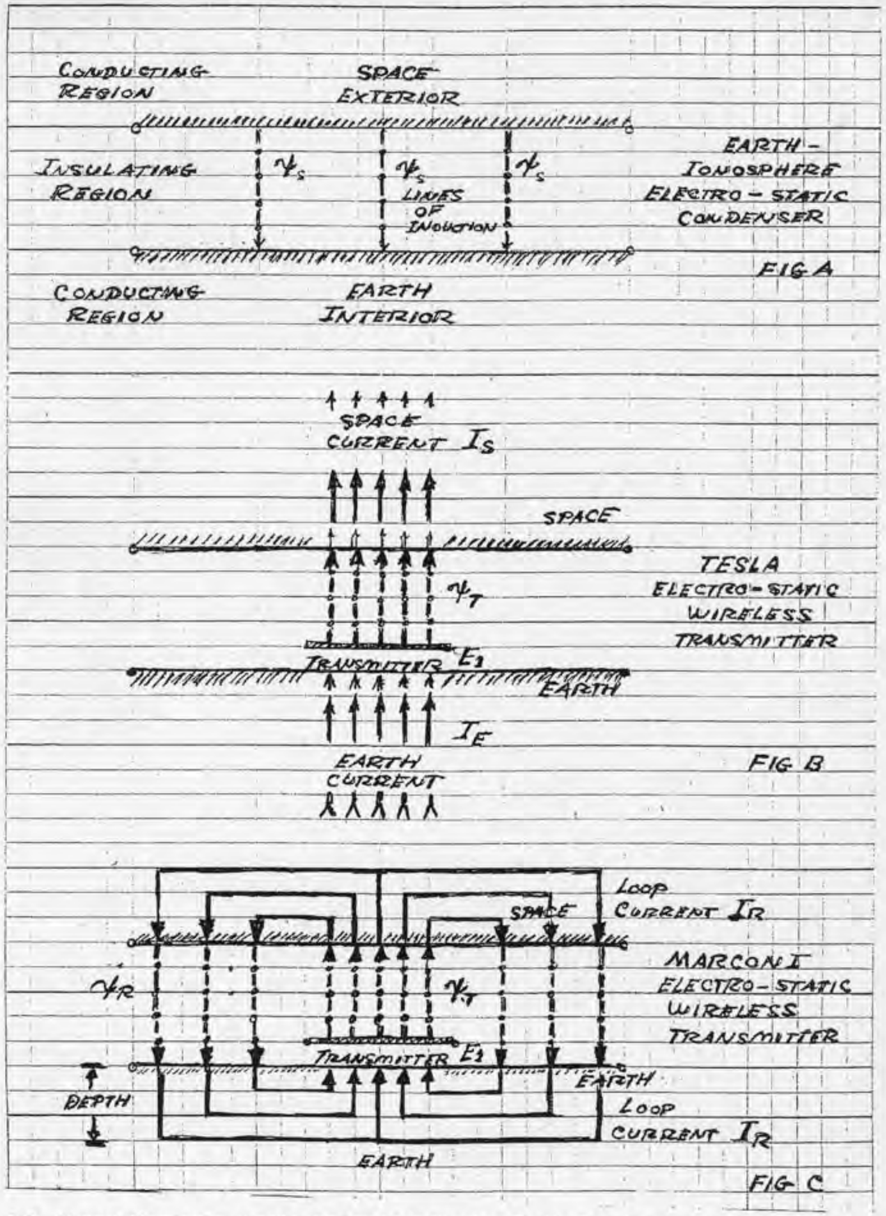


9-7 Archtypical Wireless Systems (2 diagrams) and Derivative Systems (3 diagrams)

Archetypical Systems

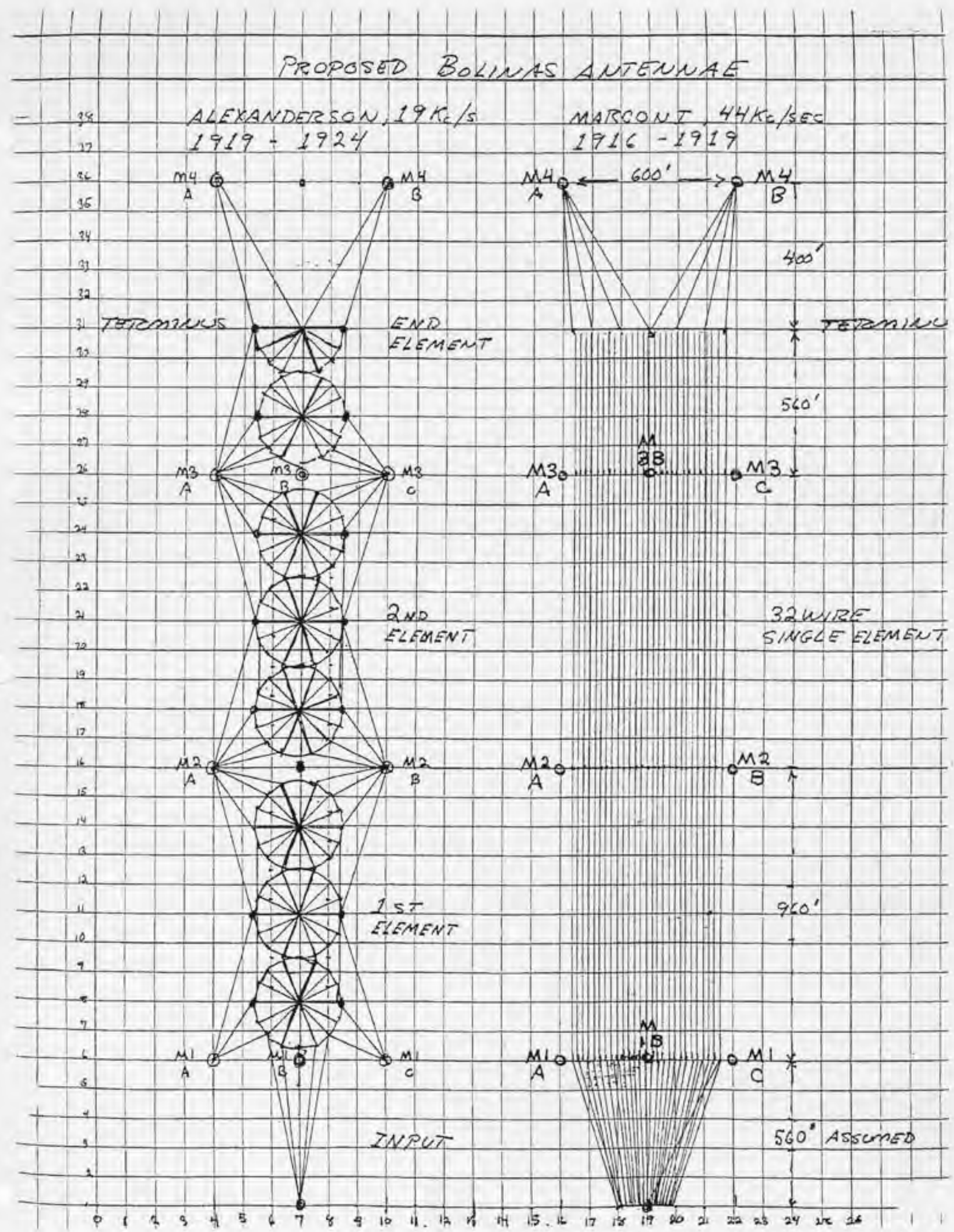


9-9 Symbolic Comparison of Electro-Static Wireless Systems – Tesla vs. Marconi



9-8 Three diagrams: "Earth-Ionosphere Electro-Static Condenser." (Fig. A); "Tesla Electro-Static Wireless Transmitter." (Fig. B); & "Marconi Electro-Static Wireless Transmitter" (Fig. C).

Electro-Static Condenser



8-2 Marconi Layout, 1916-1919 (44 Kc/sec.)

8-3 Alexanderson Layout, 1919-1924 (19 Kc/sec.)

Antenna Diagram

I)

A) The electrostatic capacity of the Bolinas array can be divided into two distinct categories:

1) That part of the electrostatic field confined between the elevated capacity and the ground plane:

$C_c = 1.5 \times 10^{-8}$ farad 0.015 uFd

2) That part of the electrostatic field which extends from the elevated capacity to space:

$C_s = 3.5 \times 10^{-9}$ farad 3500 pFd.

And therefore a total electrostatic capacity of:

$C_o = 1.9 \times 10^{-8}$ farad

With a ratio of:

$C_s : C_c = 0.35$.

And a transmission efficiency of:

$C_s : C_o = 19$ percent.

B) The electrostatic potential is given as:

$E_o = 100$ kilovolts.

With an angular velocity of:

1.2×10^5 radians per second.

Energy is supplied to this potential at a rate of:

$P = 200$ kilowatts.

Scale 1

C) For a peak potential of 100 kilovolts, the two electrostatic fields are:

1) The confined field:

$\Psi = 1.8 \times 10^{10}$ lines of force

$W = 32$ watt-second

2) And the transmitted field:

$\Psi = 4.2 \times 10^{9}$ lines of force

$W = 7$ watt-second

D) For potential variation of 1.2×10^{5} radians per second, the power flow of the two electrostatic fields are:

1) Confined power flow:

$P_c = 17 \times 10^{6}$ volt-amperes

$X_c = 6 \times 10^{2}$ sec. per farad (ohm)

2) And the transmitted power flow:

$P_s = 4.8 \times 10^{6}$ volt-amperes

$X_s = 2 \times 10^{3}$ sec. per farad (ohm)

E) The total electric current transmitted into the earth is hence given:

$I_o = 48$ amperes

With a transmission loss of 200 kilowatts and a corresponding electromotive force of:

$E_o = 4200$ volts

Scale 2

F) For the entire array the total power flow is:

$P = 21 \times 10^6$ volt-amperes

And for a dissipation rate of 200 kilowatts, the power multipaction factor is thus given:

$\wp = 100 \times$ dimensionless

II) The entire array is divided into three distinct section elements: element 1 and element 2, and a third terminal element

A) The mid-section elements are of the following electrical dimensions:

1) Electrostatic capacity to space:

$C_s = 1.4 \times 10^{-9}$	farad	1400 pFd
$P_s = 1.7 \times 10^6$	volt-amperes	
$I_s = 17$	amperes	
$X_s = 6 \times 10^3$	sec. per farad	6KΩ

2) Electrostatic capacity to ground:

$C_c = 4.9 \times 10^{-9}$	farad	4900 pFd
$P_c = 5.6 \times 10^6$	volt-amperes	
$I_c = 56$	amperes	
$X_c = 1.8 \times 10^3$	sec. per farad	1.8KΩ

3) Electromagnetic inductance:

$L = 1.3 \times 10^{-4}$	Henry
$X_L = 16$	Henry/sec. (OHM)

4) The electro-motive force developed by the electromagnetic induction of the element half-section L/2 is given by the relation:

$E_L / I_T = X$ $E = 550$ volts

And therefore, the power flow of this induction:

$E_L \times I_T =$ $P = 40 \times 10^3$ volt-amperes

And thus the ratio of magnetic to electrostatic power flow is:

$P_L : P_O = 40:7300 =$ 1.5 percent

Scale 3

B) Having derived the electromagnetic and the electrostatic coefficients of the elemental sections, the electromagnetic propagation coefficients are thus:

Z_c = transmission impedance of confined electromagnetic wave
Z_c = 173 ohm
Z_s = transmission impedance of un-confined electromagnetic wave
Z_s = 316 ohm

And likewise:

V_o = transmission velocity of confined propagation

$$V_o = 3 \times 10^{10} \quad \text{cm./sec.}$$

V_s = transmission velocity of un-confined propagation

$$V_s = 5.6 \times 10^{10} \quad \text{cm./sec.}$$

LET THE GENERALIZED ELECTRIC WAVE PROPAGATION BE REPRESENTED BY THE FOLLOWING FIGURE;

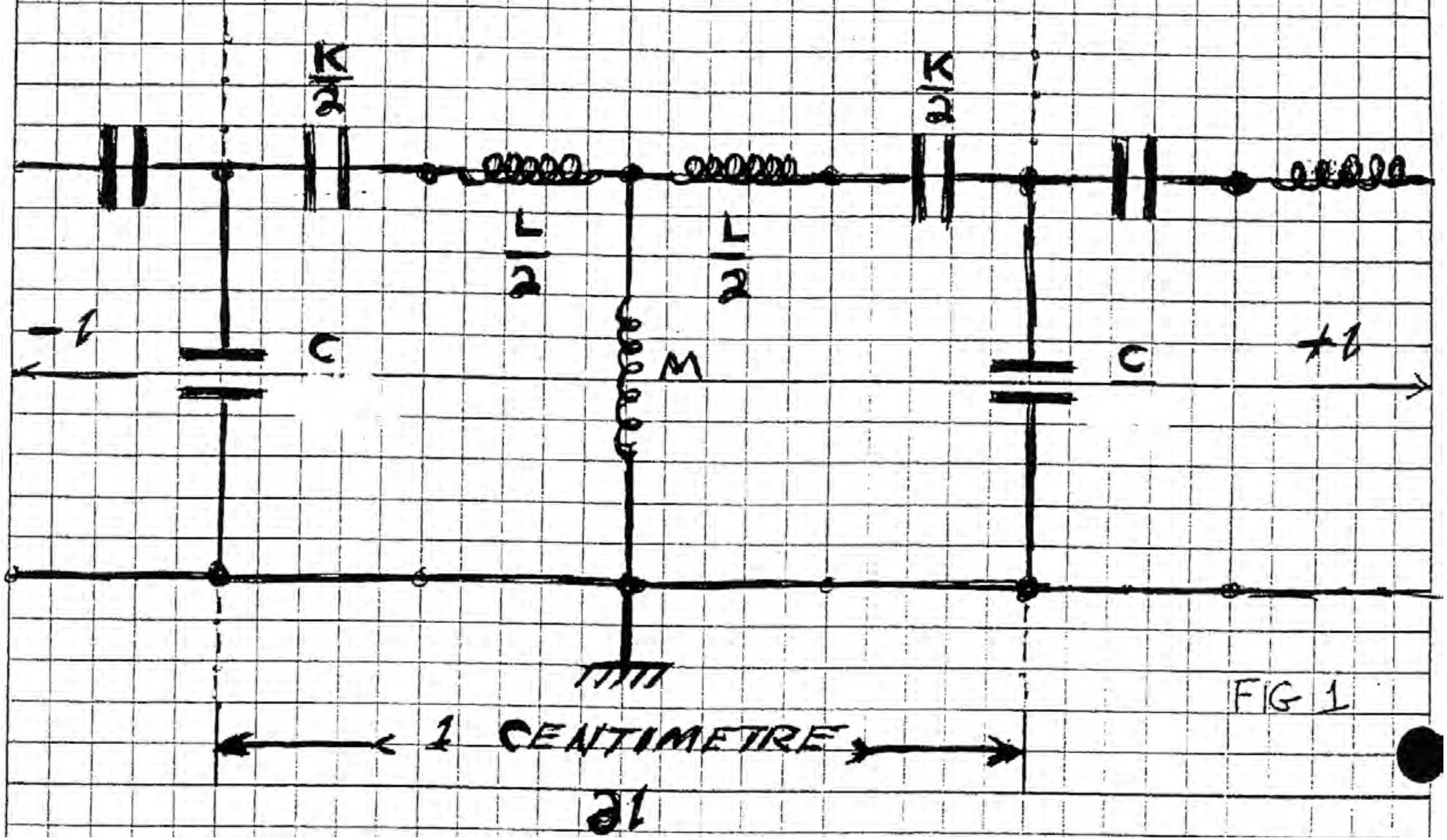


FIG 1

WHERE

C IS THE COEFFICIENT OF DIELECTRIC INDUCTION TRANSVERSE TO THE DIRECTION OF PROPAGATION IN FARADS PER CENTIMETRE,

K IS THE COEFFICIENT OF DIELECTRIC INDUCTION LONGITUDINAL WITH THE DIRECTION OF PROPAGATION IN PER FARAD CENTIMETRE,

L IS THE COEFFICIENT OF MAGNETIC INDUCTION TRANSVERSE TO THE DIRECTION OF PROPAGATION IN HENRYS PER CENTIMETRE,

M IS THE COEFFICIENT OF MAGNETIC INDUCTION LONGITUDINAL WITH THE DIRECTION OF PROPAGATION IN PER HENRY CENTIMETRE

These coefficients are defined by the established conventional physical dimensions

$$C = \frac{t^2}{l^3} \qquad \text{sec}^2 \text{ per cm}^3 \qquad (1)$$

$$K = \frac{l}{t^2} \qquad \text{cm per sec}^2 \qquad (2)$$

$$L = l \qquad \text{cm} \qquad (3)$$

$$M = \frac{1}{l^3} \qquad \text{per cm}^3 \qquad (4)$$

Let the shunt coefficients be combined by the relation

$$M + u^2 C = M + \frac{1}{(k\omega)^2} C \qquad (5)$$

And let the series coefficients be combined by the relation

$$K - u^2 L = K - \frac{1}{(k\omega)^2} \qquad (6)$$

Where the factor

$u^{-2} = (k\omega)^{+2}$ per second^2 (7)

and

$\omega = 2\pi F$ per second

$k^4 = -1$ A dimensionless unit

THE PRODUCT OF EQ (5) & EQ (6) GIVES THE COMPLETE ALGEBRAIC EXPRESSION OF THE ELEMENTAL SECTION IN FIGURE (1)

$$\left(M+u_{I}^{2}C\right)\left(K-u_{II}^{2}L\right)=\Gamma^{4} \qquad (8)$$

AND CARRYING THRU THE PRODUCTS GIVES THE RELATION

$$\Gamma^{4}=\left[MK+\left(u_{I}^{2}u_{II}^{2}\right)LC\right]+\left[u_{I}^{2}CK-u_{II}^{2}LM\right] \qquad (9)$$

EQ (9) REPRESENTS THE FOURTH ORDER DIFFERENTIAL EQUATION OF THE COMPLEX PROPAGATION THRU THE ELEMENT, FIG (1).

IT WILL BE SEEN THAT EQ (9) IS DIRECTLY ANALOGOUS WITH THE HEAVISIDE TELEGRAPH EQUATION,

$$(R + u_0 L)(G - u_0 C) = \Gamma^2$$

$$= (RG + u_0^2 LC) + u_0 (LG - RC) \quad (10)$$

WHERE

R IS THE SERIES RESISTANCE IN OHMS PER CM

AND

G IS THE SHUNT CONDUCTANCE IN PER OHM CM

THE FOUR COMPONENTS OF EQ (9) ARE THUS,

I) MK REPRESENTS THE LONGITUDINAL WAVE OF ELECTRIC INDUCTION, AND BY EQ (2), (4) IT IS DEFINED

$$MK = 1/l^2t^2 \quad \text{, PER } CM^2 SEC^2 \qquad (11)$$

II) LC REPRESENTS THE TRANSVERSE WAVE OF ELECTRIC INDUCTION, AND BY EQ (1), (3) IT IS DEFINED

$$LC = t^2/l^2 \quad \text{, } SEC^2 \text{ PER } CM^2 \qquad (12)$$

III) CK REPRESENTS THE DISTRIBUTION OF DIELECTRIC INDUCTION, AND BY EQ (1), (2) IT IS DEFINED

$$CK = 1/t^2, \quad \text{PER CM}^2 \qquad (13)$$

IV) LM REPRESENTS THE DISTRIBUTION OF MAGNETIC INDUCTION, AND BY EQ (3), (4) IT IS DEFINED

$$LM = 1/t^2, \quad \text{PER CM}^2 \qquad (14)$$

THE INTERACTION OF THE LONGITUDINAL WAVE (MK) WITH THE TRANSVERSE WAVE (LC) IS REPRESENTED BY THE FACTORS u_{1}^{2} & u_{11}^{2} WHERE,

$L/K = \omega_{1}^{-2}$ REPRESENTS THE TIME CONSTANT OF THE SERIES COEFFICIENTS AND BY EQ (2), (3) IT IS DEFINED

$$L/K = \text{PER SEC}^{-2} \tag{15}$$

$C/M = \omega_{11}^{-2}$ REPRESENTS THE TIME CONSTANT OF THE SHUNT COEFFICIENTS AND BY EQ(1), (4)

C/M = PER SEC^{-2} (16)

THE FACTOR (MK) REPRESENTS WAVE PROPAGATION THRU COUNTER SPATIAL DISTANCE, PER CM. OVER TIME PERIOD, SEC.

THE FACTOR (LC) REPRESENTS WAVE PROPAGATION THRU SPATIAL DISTANCE, CM. OVER TIME PERIOD, SEC.

THE FACTOR (CK) DOES NOT PROPAGATE, BUT IS A DISTRIBUTION OVER DISTANCE CM, AND LIKEWISE LM DOES NOT PROPAGATE, BUT IS A DISTRIBUTION OVER DISTANCE CM. THESE FACTORS ARE TIME SCALARS, THAT IS, NO VARIATION EXISTS IN THE DIMENSION OF TIME.

THE FACTOR (L/K) OSCILLATES WITH NO VARIATION OVER DISTANCE CM., AND LIKEWISE (C/M) OSCILLATES WITH NO VARIATION OVER DISTANCE. THESE FACTORS ARE FREQUENCIES, OR TIME FACTORS OF SEC^{-1} AND ARE SPACE SCALARS.

IN TERMS OF CIRCUIT ELEMENTS THESE TERMS ARE REPRESENTED BY

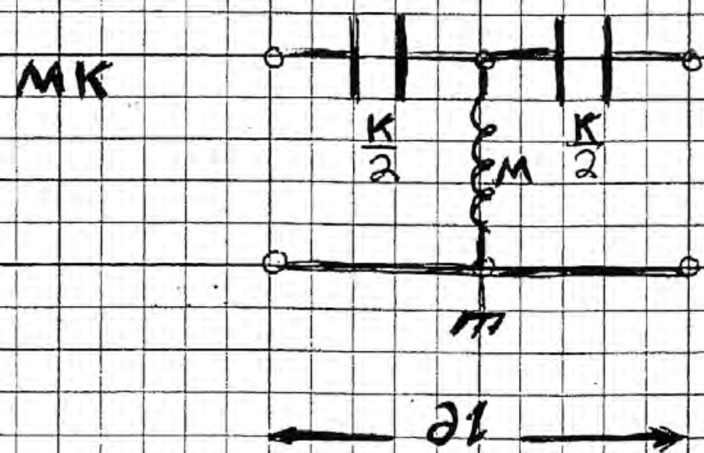


FIG (2)

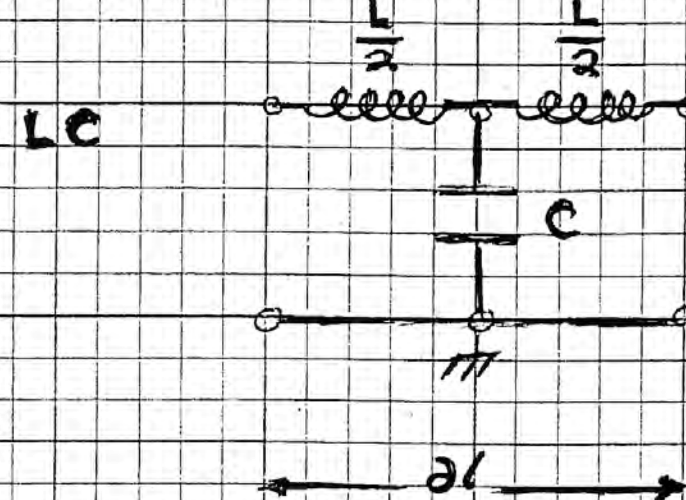


FIG (3)

(MK) CAN BE SEEN AS A FUNDAMENTAL HIGH PASS SECTION OR PHASE LEAD NETWORK, AND BECOMES TRANSPARENT TO PROPAGATION FOR

$$\partial/\partial t \rightarrow \infty$$

(LC) CAN BE SEEN AS A FUNDAMENTAL LOW PASS SECTION OR PHASE LAG NETWORK, AND BECOMES TRANSPARENT TO PROPAGATION FOR

$$\partial/\partial t \rightarrow 0$$

LIKEWISE

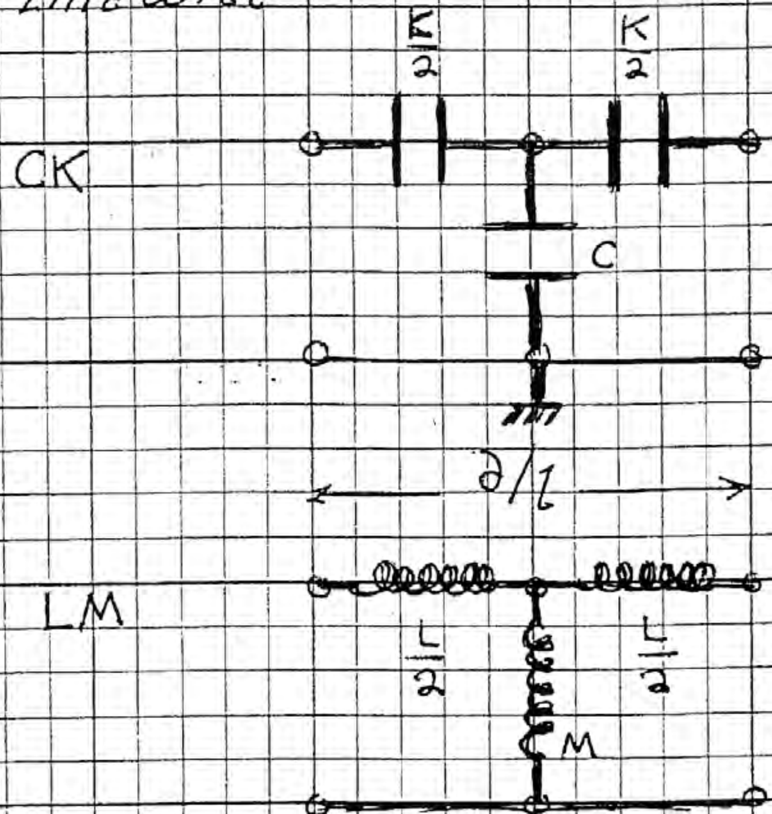


FIG (4)

WHERE (CK) & (LM) DO NOT PROPAGATE BUT ARE INSTANTANEOUS DISTRIBUTIONS OF THE DIELECTRIC & MAGNETIC FIELDS OF INDUCTION RESPECTIVLY. INSTANTANEOUS ACTION IS CARRIED THRU K IN THE DIELECTRIC DISTRIBUTION & M IN THE MAGNETIC DISTRIBUTION. AND FINALLY

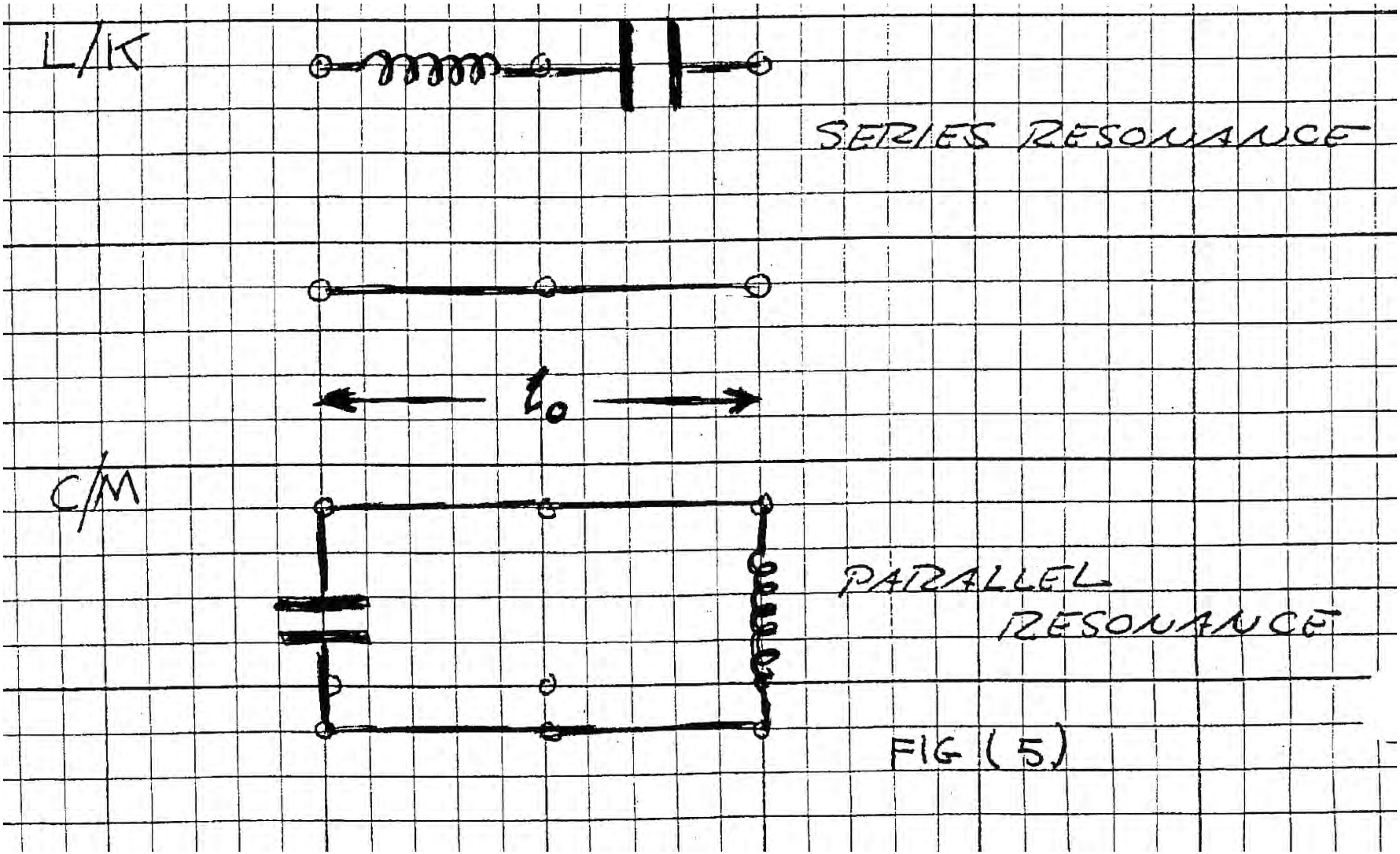


FIG (5)

WHERE (L/K) & (C/M) DO NOT PROPAGATE BUT ARE THE SERIES & PARALLEL RESONANT FREQUENCIES OF THE ENTIRE ELECTRICAL NETWORK OF LENGTH l_0.

IN GENERAL ANY ELECTRICAL NETWORK OF THE FORM IN FIG (1) WILL EXIBIT A PAIR OF FREQUENCIES WHICH MAY BE DISSONANT OR CONSONANT DEPENDING ON THE RELATION BETWEEN (LM) AND (CK.) IF SUCH A NETWORK IS TERMINATED IN ITS IMAGE IMPEDANCE & ADMITTANCE IT WILL EXHIBIT A BAND PASS CHARACTERISTIC PASSING A DEFINITE WINDOW OF FREQUENCIES.

THE FREQUENCIES WILL BE IN UNISON IF THE CONDITION

$$L/K = C/M \qquad (17)$$

EXISTS, OR TRANSPOSING,

$$LM = CK \qquad (18)$$

THAT IS, IF THE DISTRIBUTION OF MAGNETIC INDUCTION EXACTLY MATCHES THE DISTRIBUTION OF DIELECTRIC INDUCTION, THE NETWORK IS THEN DISTORTIONLESS.

CONVERSELY, IF (L/K) OR (C/M) IS MADE TO VANISH, LEAVING ONLY ONE OR THE OTHER, SUCH AS WITH CADUCEOUS WOUND NETWORKS OR LUMPED CONSTANTS ONLY A SINGLE FREQUENCY EXISTS AND THE NETWORK IS SPACE SCALAR.