Copyright © 1974 American Telephone and Telegraph Company
THE BELL SYSTEM TECHNICAL JOURNAL
Vol. 53, No. 9, November 1974
Printed in U.S.A.

Outage of the L4 System and the Geomagnetic Disturbances of 4 August 1972

By C. W. ANDERSON III, L. J. LANZEROTTI, and C. G. MACLENNAN

(Manuscript received April 24, 1974)

An outage of the Plano, Illinois, to Cascade, Iowa, link of the L4 coaxial cable occurred at about 2240 UT on 4 August 1972 during a large geomagnetic storm. The available geomagnetic data measured in North America, as well as data received from two satellite instruments, are analyzed. These data show that, at the time of the L4 outage, the boundary of the magnetosphere was pushed to unusually low altitudes by a greatly enhanced solar wind. As a result, large, rapid changes of the earth's magnetic field strength were observed over North America. It is demonstrated that the field changes at about 2241 to 2242 UT were of such magnitude as to induce earth currents of sufficient strength to produce the L4 outage by causing a high-current shutdown of the system link. The geomagnetic disturbances that produced the shutdown were not of the auroral-electrojet type normally associated with disruptions of power systems.

I. INTRODUCTION

The solar and geomagnetic disturbances resulting from solar active region 11976 were truly outstanding in many regards. The principal solar region of the activity was in the highest solar activity class on an absolute scale; this major solar activity occurred during the declining phase of the 11-year solar cycle.[1] The solar disturbances, propagating outward into interplanetary space, produced the largest galactic cosmic ray decrease on record.[2] The geomagnetic storms (with accompanying ionospheric and auroral disturbances) resulting from the interaction of the propagating solar disturbances with the earth's magnetosphere were the most severe recorded in well over a decade.

The interaction of the greatly enhanced solar wind[3] with the earth's magnetic field on 4 August 1972 produced extreme compressions and distortions of the magnetosphere. It was during the period of the most severe magnetospheric distortion that an outage of the L4 coaxial cable carrier system occurred over the link from Plano, Illinois, to Cascade, Iowa. This paper, utilizing most of the available North American geomagnetic data, describes the geophysical occurrences and conditions at the time of the L4 outage. These data, plus magnetic field data from two satellites, demonstrate that the L4 outage was associated with the extreme compressions and distortions of the magnetosphere and not simply with greatly enhanced auroral currents, as are often assumed in discussions and models of magnetic storm-induced power-system disruptions.[4] The North American geomagnetic data are used as input to a model for the calculation of currents induced in the earth by the geomagnetic disturbances. It is shown that these earth currents were sufficient to produce a shutdown of the L4 system.

II. GEOMAGNETIC OCCURRENCES

The subsequent discussions of the available geomagnetic data during the August 1972 storm period must be placed in the perspective of normal magnetospheric conditions. Figure 1 is a view of the earth's magnetosphere in the equatorial plane. The distance from the earth's surface to the magnetospheric boundary is approximately $9R_E$ ($1R_E \approx 6.5 \times 10^3$ km) for normal solar wind density conditions of ≈ 5 protons cc^{-1}. Figure 1 also shows the circular, earth-synchronous satellite orbit at an altitude of $\approx 5.5R_E$, which is occupied by all common-carrier communications satellites. For later reference, the location of the NASA synchronous altitude Applications Technology Satellite 5 (ATS 5) at 2200 UT is indicated. Also indicated, for the same UT, is the apogee location of the near-equatorial, elliptical-orbit satellite Explorer 45.[5]

The approximate geomagnetic latitude and longitude of Plano, Illinois (50.8°N, 336.8°E) are shown on the earth in Fig. 1 for 2200 UT. Also indicated on the earth are the locations of several North American magnetic observatories: Meanook (61.81°N, 301.07°E), Churchill (68.69°N, 322.63°E), and Ottawa (56.80°N, 351.52°E). All geomagnetic stations used in this study are listed in Table I, together with their coordinates.

Acquisition of sufficient geomagnetic data for a definitive analysis of the geomagnetic effects of the storm in North America was made difficult by the inability of most magnetic observatory instruments to record the very large and rapid variations that occurred during the hour 22 UT on 4 August. Because of the instruments' limitations, it is likely that many of the actual variations were larger than those

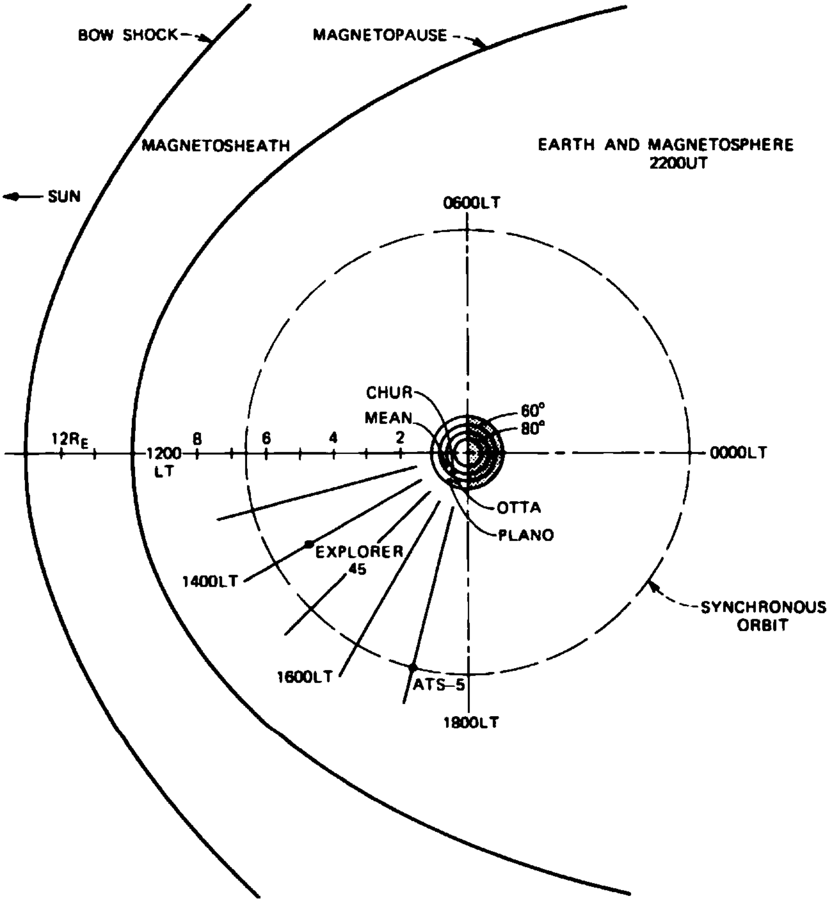

Fig. 1—View of earth and magnetospheric configuration in equatorial plane under normal solar wind flow conditions.

used in this paper.[6] Indeed, for the analysis of the 20-minute interval (2230 to 2250 UT, 4 August), around the time of the L4 outage, data at one-minute time intervals could be scaled from the continental U. S. and Alaska standard observatory chart records for only the observatories at College, Sitka, Tucson, and Fredericksburg. Scalings of 2½ minutes were obtained from observatories at Castle Rock and Dallas. Scalings of 1 minute were obtained from a special National Oceanic and Atmospheric Administration station near Boulder. Fortunately, the Earth Physics Branch of the Department of Energy, Mines,

Table I

Geomagnetic Station	Geomagnetic Coordinates	
	Lat(°N)	Long(°E)
Baker Lake	73.74	315.31
Boulder	48.85	316.44
Cambridge Bay	77.7	300.3
Castle Rock	43.48	298.62
College	64.66	256.51
Dallas	42.96	327.75
Fredericksburg	49.55	349.84
Fort Churchill	68.69	322.63
Meanook	61.81	301.07
Ottawa	56.80	351.52
Sitka	60.00	275.34
St. Johns	58.50	21.24
Tucson	40.03	311.41
Victoria	54.08	293.04

and Resources in Ottawa was operating a number of digital-recording magnetometers in Canada during 1972.[6] These data have greatly facilitated our analysis of the magnetic disturbances. Most of the available U. S. magnetometer data were obtained from the World Data Center A and were scaled for us by the Geophysical Institute of the University of Alaska.

Plotted in Fig. 2 are the magnetic variations measured in the north-south (H or X) and east-west (D or Y) orthogonal directions at the three Canadian observatories, Meanook, Churchill, and Ottawa, during the time interval 2200 to 2300 UT on 4 August. At the bottom of both sets of data is plotted the magnetic field trace of the Z-component recorded by a magnetometer on the ATS 5 satellite.[7] The Z-component of the magnetic field at the ATS 5 location is measured parallel to the earth's spin axis.

The data plotted in Fig. 2 show particularly large field changes occurring during the several-minute time interval following 2240 UT. For example, at about 2242 UT, the field change $\Delta H/\Delta t$ measured at Meanook was $\approx$ 1800 γ/min. ($1\gamma = 10^{-5}$ gauss). The field data from the ATS 5 satellite are particularly interesting in that, at $\approx$ 2225 UT and $\approx$ 2240 UT, the field direction reversed. At $\approx$ 2241 UT, the field intensity was $\approx -400\gamma$; i.e., the measured field pointed in a direction opposite to that of the normal dipole field. At $\approx$ 2242 UT, the field direction at ATS 5 suddenly became normal; at this time, $\Delta Z/\Delta t$ at ATS 5 was $\approx$ 575 γ/min.

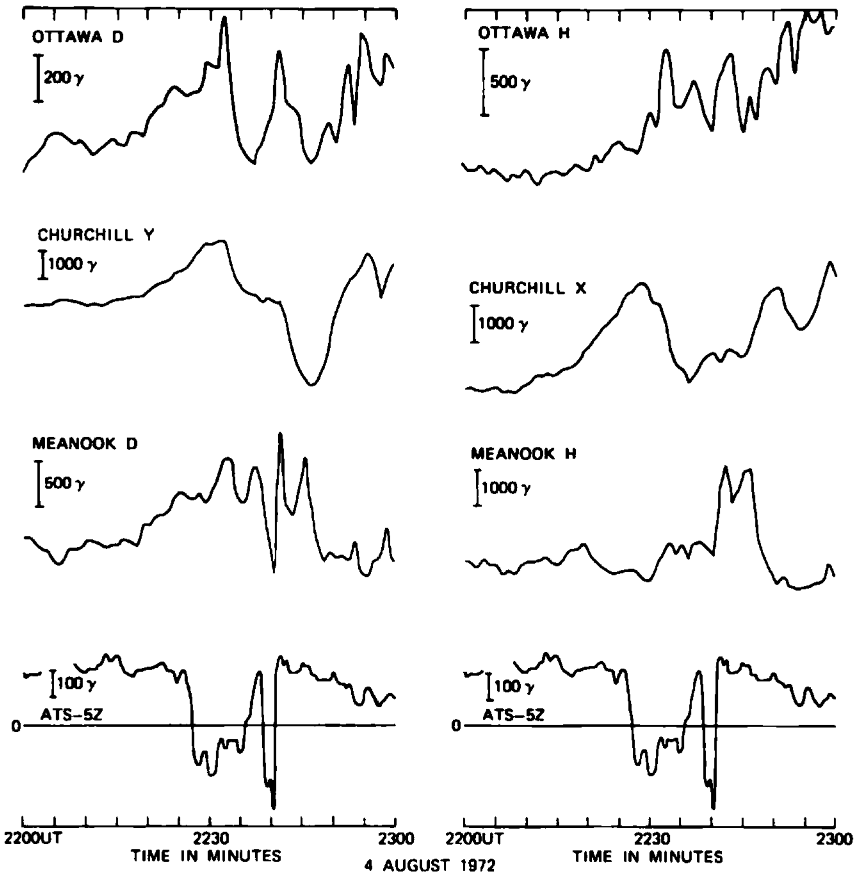

Fig. 2—Magnetic field variations observed at three Canadian observatories (Meanook, Churchill, and Ottawa) in north-south and east-west directions during the hour 2200 to 2300 UT on 4 August 1972. Plotted beneath each set of data are the variations in the field observed near the equator on the ATS-5 spacecraft.

Reversals of the earth's field direction, similar to those shown in Fig. 2, have been observed in the past by magnetometers on the ATS 1[8] and ATS 5[9] satellites. These occurrences have been attributed to a movement of the magnetopause to a location *inside* the orbit of the synchronous satellite, which then measures the magnetic fields in the earth's magnetosheath region. The complex particle and field changes that occur in the magnetosphere during such a "boundary-crossing" event have been discussed in a series of papers devoted to extensive study of one such event.[8,10–13]

The distortions of the magnetospheric boundary as evidenced by the boundary-crossing event observed on ATS 5 on 4 August 1972 were accompanied by the large geomagnetic field changes observed on the ground in North America. It is interesting to note that the study of several boundary crossing events on ATS 5[9] suggested that the largest effects were observed on the ground when the magnetosphere distortion occurred in the local afternoon side of the magnetosphere rather than in the local morning side of the magnetosphere. For the 4 August event, no local morning data are available from a synchronous satellite. However, the magnetosphere distortions that were observed were in the local afternoon sector.

The one-minute values of the magnetic field changes [$H(X)$ and $D(Y)$ components] that could be determined from North American observatory data were used to make contour maps of the field changes at one-minute intervals in the U. S. and Canada. These contours for 2238 to 2243 UT are plotted in Figs. 3a and 3b in a geomagnetic coordinate system. Because of the spread in distance between observatories and the impossibility of obtaining a reliable magnetic field reading from the chart records of several observatories, the locations of some contour lines in Figs. 3a and 3b are, at best, extrapolations. For lack of a better justified procedure, the contours have been constructed on the basis of linear interpolation between observatory field values. It should be noted that, for more conventional magnetic disturbances arising from auroral electrojet current systems, the fall-off in magnetic disturbances from higher to lower latitudes is nonlinear; i.e., the disturbance level falls off more rapidly at the lower latitudes. The changes in the location and intensity of the magnetic disturbances from the relatively undisturbed period at $\approx$ 2238 UT until the large disturbance at Meanook at $\approx$ 2242 UT is quite evident in the contours of Figs. 3a and 3b.

There is evidence in the contours of Figs. 3a and 3b of perhaps some progression of the geomagnetic disturbance from the higher to the lower latitudes. For example, in the interval 2240 to 2241 UT the disturbance change is largest at College, while in the interval 2241 to 2242 UT the disturbance change becomes largest at Meanook. If this progression of the disturbance is associated with a distortion and compression of the magnetospheric boundary to smaller radii (and therefore lower latitudes), the contours suggest that the boundary compression may have reached field lines that intersect with latitudes as low as that of Meanook. That this was apparently the case is discussed below.

Plotted in Fig. 4 as contours (linear interpolations) on a geographical map of North America are the magnitudes of the total horizontal field changes and the angles [from the $D(Y)$ direction] of the changes measured between 2241 and 2242 UT, at about the time of the sudden changes in the apparent ATS 5 location from the magnetosheath to the magnetosphere (see Fig. 1). At this time, the field intensity at Plano is interpolated to be $\approx 700\gamma$ and the field change is aligned in an approximately NE–SW direction. These are the important geomagnetic parameters that will be used in the next section to calculate the expected induced earth currents at Plano.

Before calculating the earth currents however, it is of interest to further examine the magnetospheric environment at ≈ 2241 UT. At about this time, the Explorer 45 satellite was located at its apogee position and was about two hours closer to local noon than ATS 5 (see Fig. 1). Magnetic field data and charged-particle data from Explorer 45 indicate that, at ≈ 2242 UT, when the magnetosphere boundary expanded outward beyond ATS 5, a movement of the boundary inward, inside Explorer 45, was recorded.[14] Inspection of the magnetograms from College, near local noon, at ≈ 2241 UT indicate that the field increased in magnitude and that the field changes were predominantly in the H direction (see Fig. 2). This observation also suggests a compression of the magnetosphere boundary near local noon.

Hence, summarizing and synthesizing as well as possible the available magnetospheric data, the boundary of the magnetosphere in the local afternoon sector at ≈ 2240 and ≈ 2242 UT could be pictured as in Fig. 5. Not only is the boundary greatly compressed from the normal location (see Fig. 1), but it is also highly distorted as evidenced by the simultaneous observations of the magnetopause at altitudes higher than ATS 5 but lower than Explorer 45 at ≈ 2242 UT. This observation by Explorer 45 provides evidence of the most compressed position of the magnetopause yet recorded. The extreme compression and distortion of the magnetosphere recorded in the sector above the western hemisphere at ≈ 2242 UT was undoubtedly the primary cause for the large magnetic field changes recorded in North America at the time.

III. TELLURIC DISTURBANCES

To put into perspective the analysis used to calculate the induced earth currents at Plano, it is of interest to review the basic relationships between earth resistivity structure, geomagnetic disturbances,

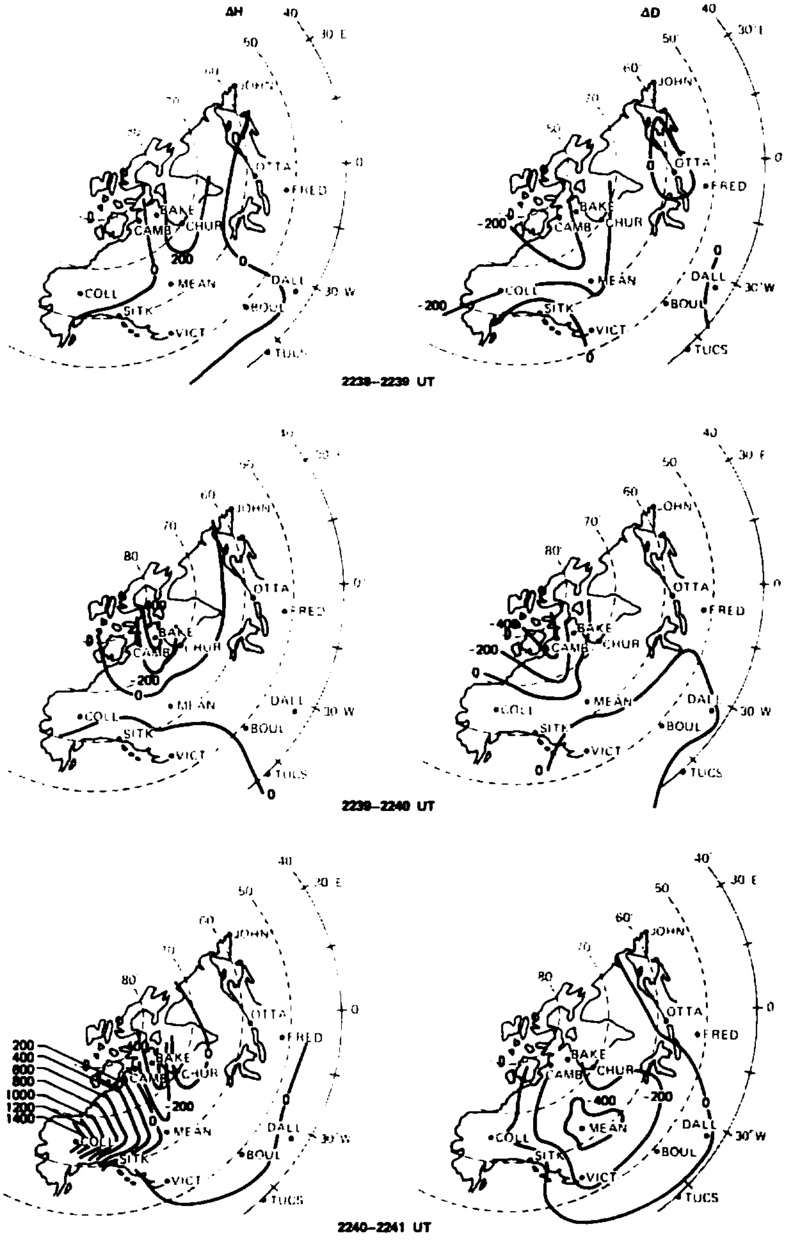

Fig. 3a—Minute-by-minute rate of change of magnetic field in the horizontal plane over North America from 2238 to 2241 UT.

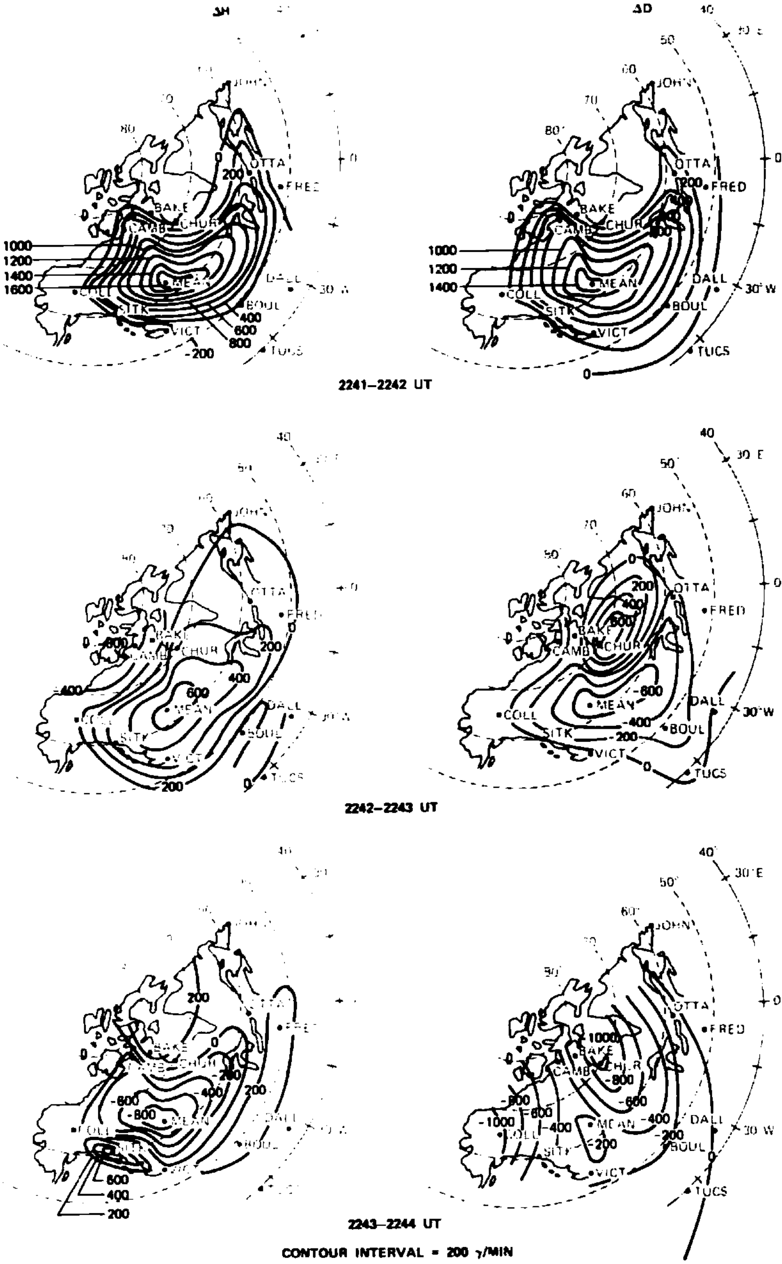

Fig. 3b—Minute-by-minute rate of change of magnetic field in the horizontal plane over North America from 2241 to 2244 UT.

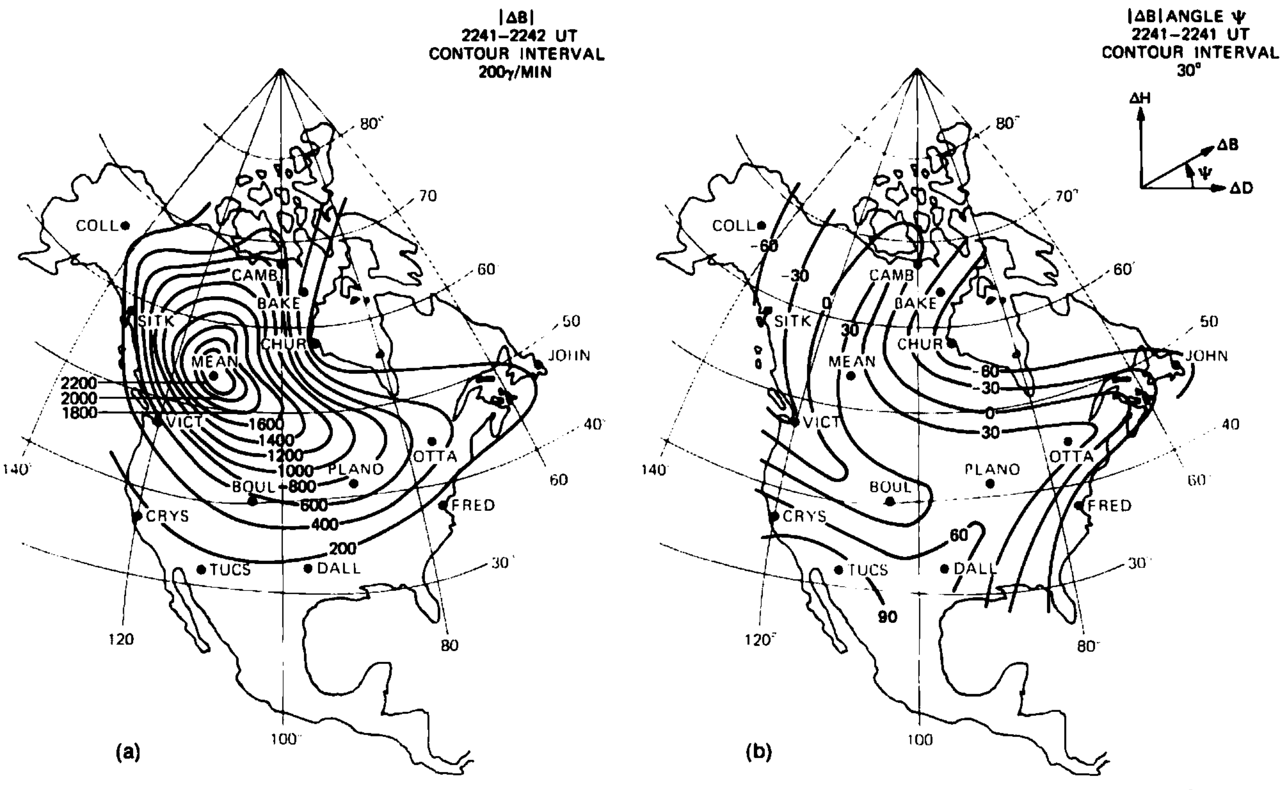

Fig. 4—Rate of change of magnetic field intensity and direction over North America for the one-minute interval 2241 to 2242 UT.

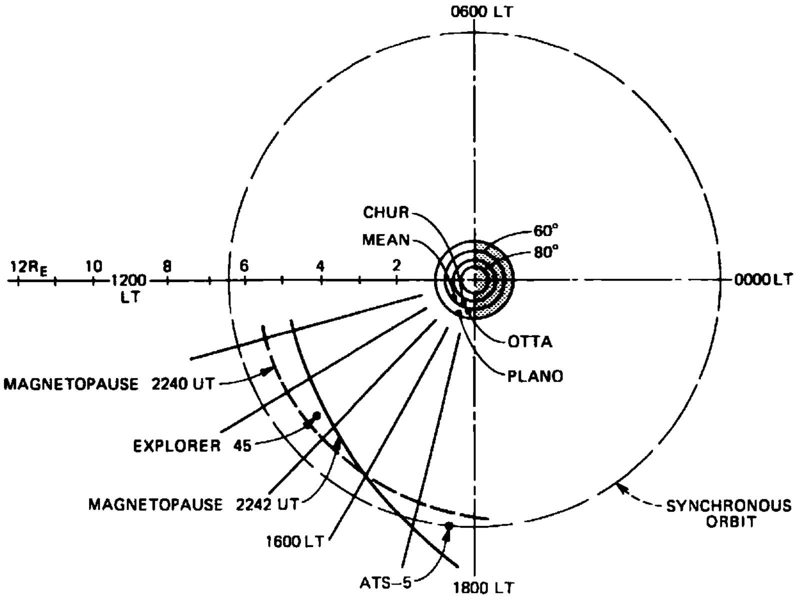

Fig. 5—Equatorial plane view of earth and magnetospheric boundary in afternoon sector at 2240 UT and 2242 UT.

and telluric disturbances; i.e., induced electric fields at the earth's surface.

The basic theory of tellurics is contained in a boundary value problem involving Maxwell's equations and the resultant electromagnetic wave equation. An external exciting source is assumed. The phase and amplitude relationships between the orthogonal components of the horizontal electric and magnetic fields observed at the surface of the earth are measures of the electrical properties of the earth.

Electromagnetic induction by a uniform horizontal magnetic field B [with components H(NS) and D(EW)] in a uniform semi-infinite earth produces orthogonal horizontal electric fields, E, which satisfy the following relationships:[15]

$$\text{mod}\ (E/B) \propto 1/T^{\frac{1}{2}} \tag{1a}$$

$$\arg\ (E/B) = \pi/4, \tag{1b}$$

where T is the period of the magnetic field B. Hence, the ratio of the amplitude of the electric field to the magnetic field is proportional to the inverse square root of the period T and the phase difference is always $\pi/4$.

It is necessary to measure three mutually orthogonal components in order to completely describe the vector magnetic field. It is customary in land-based magnetic variation surveys at midlatitudes to measure the horizontal H (geomagnetic NS) varying, horizontal D (geomagnetic EW) varying, and vertical Z components of the magnetic field. The sense of the variations is positive north for H, positive east for D, and positive down for Z. The fields are referenced from the earth's surface and magnetic north. The induction process, therefore, is such that a positive H variation will produce an east-to-west flowing telluric current (a negative surface electric field). [At high latitudes it is customary to use the geographic NS (X) and geographic EW (Y) components.]

Telluric current observations, together with the magnetic field measurements, usually show that the amplitude ratio E/B is proportional to the inverse square root of the period. Thus, the relationship in eq. (1a) suggests the use of a uniform conductivity earth model. However, observations of the phase differences between E and B seldom agree with the predictions of the uniform earth model (1b). Phase differences as small as 20° for magnetic field variations with periods of 20 to 30 minutes and as large as 45° for much shorter periods have been reported.[15] These large discrepancies in phase differences between the theory and the observations underscore the fact that a uniform earth model is seldom applicable to the real earth at an observing location.

Wait[16] has developed an analytical formulation of the electromagnetic fields of an infinite line source above a horizontally stratified earth. The earth model can be extended to include any number of layers. The line source can serve as an equivalent current system to the real current systems (e.g., ionospheric or magnetospheric current systems), which can produce natural electromagnetic fields at the earth's surface. The basic relationship between the electric and magnetic fields at the surface of the earth is given as[15]

$$\frac{-\mu_o E_y}{H} = Z_1, \tag{2}$$

where μ_o is the free space permeability and Z_1 is defined as the surface impedance. For a three-layer earth model, the surface impedance is given as[16]

$$Z_1 = \frac{i\mu_o\omega}{u_1} Q, \tag{3}$$

where u_1 is the propagation constant for the first layer, μ_o is the free space permeability, ω is the angular frequency, and Q is a correction term that accounts for the resistivities and thicknesses of the three layers. The mks system is used throughout.

The surface impedance defines the relationships between the tangential electric and magnetic fields at the earth's surface. The surface impedance also completely represents the electrical properties of the earth, when displacement currents are neglected. Estimates of the surface impedance can be made from knowledge of the geology in a specific area.

The apparent resistivity of the three-layer earth model is related to the surface impedance by the expression[14]

$$\rho_a(\omega) = \frac{1}{\omega\mu_o}|Z_1(\omega)|^2. \tag{4}$$

The apparent resistivity ρ_a (in ohm-meters) is highly dependent on the angular frequency ω of the source and the conductivity structure of the three-layer earth. It is important to note that many published values of earth resistivity are, in fact, apparent resistivities that are valid only in a limited frequency range. For example, the use of earth resistivity values determined at 60 Hz will not normally be valid at the frequencies at which telluric currents are important (see Fig. 7).

The numerical evaluation of eq. (2) is substantially simplified if the electromagnetic fields are considered plane waves. Since no physical sources exist in nature that produce plane waves, it is necessary to determine the range of frequencies and geographic conditions in which the fields of a line source can be successfully approximated by mathematical plane waves.

Peeples[17] has shown that the plane wave approximation will be valid for wave periods less than 500 seconds for earth models that have a highly conducting sedimentary first layer, if the line current is located at a height of at least 100 km. Morrison[18] has shown that, as the resistivity of the first layer increases, the period range decreases for which a plane wave analysis is valid. The plane wave approximation has been found valid in the frequency range ($\approx$0.01 to 0.1 Hz) in which telluric current effects are important to long-haul communication systems. Hence, the surface impedance and apparent resistivity for a plane wave can be readily computed from eqs. (3) and (4) once the parameters of the three-layer earth are established. The surface electric field can be computed for any value of the magnetic induction field by inserting the appropriate surface impedance value into eq. (2).

IV. PLANO EARTH RESISTIVITY MODEL

In this section, a three-layer earth resistivity model is developed. The model is derived from the modified Cantwell-McDonald earth resistivity model[19] and detailed information of the geology[20] in the vicinity of Plano, Illinois. This model is assumed to be representative of the entire L4 route from Plano, Illinois, to Cascade, Iowa.

Geophysical studies in the vicinity of Plano indicate that the granitic basement rocks are at a depth of about 1.2 km. Above the basement lies a relatively thick sequence of flat-lying sedimentary rocks consisting of Cambrian and Ordovician sandstones, shales, and dolomites. Unconsolidated glacial deposits overlie the bedrock with thicknesses of 18 to 36 meters.

The three-layer earth model in Fig. 6 was arrived at by merging the upper crustal model with the modified Cantwell-McDonald earth resistivity model. Because of the relatively low frequencies encountered in telluric studies, it was felt that the layer of unconsolidated glacial deposits could be ignored without affecting the results.

The top layer of sedimentary rocks was given a resistivity of 100 Ωm and a thickness of 1.22 km; the second layer of granitic basement rock was given a resistivity of 5000 Ωm and a thickness of 300 km; the bottom layer, representing the upper mantle, was given a resistivity of 10 Ωm and an infinite thickness. The surface impedance was computed using the earth parameters from Fig. 6 in eq. (3) after modification of the latter for the plane wave approximation.

The more familiar apparent resistivity, which is related to the surface impedance through eq. (4), was determined to show the frequency

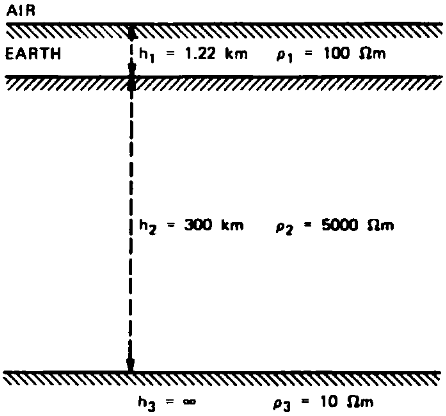

Fig. 6—Three-layer resistivity model for Plano, Illinois, vicinity.

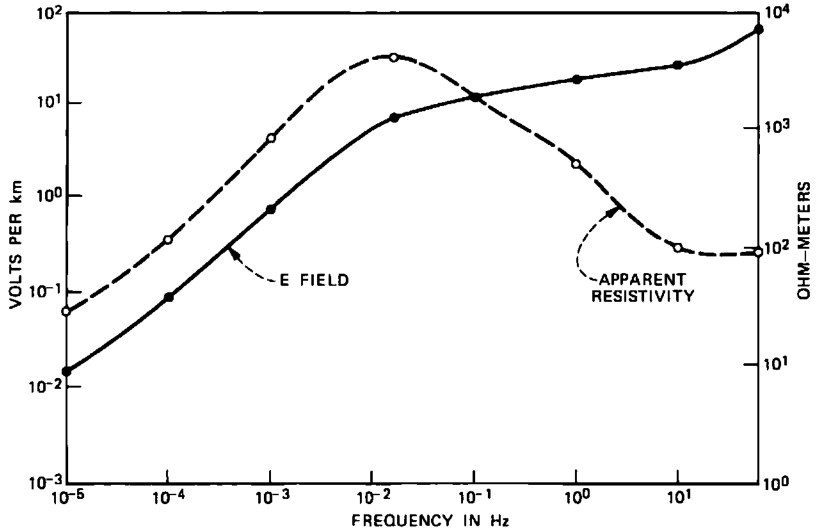

Fig. 7—Variation with frequency of apparent resistivity and surface electric field for the three-layer model of Fig. 6.

response of the earth model. Figure 7 illustrates the variation in apparent resistivity as a function of frequency. The decrease in the apparent resistivity at the higher frequencies arises from the influence of the top layer. A maximum apparent resistivity is shown at about 10^{-2} Hz; this reflects the influence of the highly resistive second layer, the basement rock. The drop in apparent resistivity below $\approx 10^{-2}$ Hz arises from the influence of the less resistive upper mantle as the frequency decreases and the depth of penetration of the magnetic field increases. Hence, in this layered earth model, there are certain frequencies for which the apparent resistivities are much higher than others. Earth resistivity models in general are nonunique, and extrapolations from them should be done with caution.

The surface impedance based on the above earth model was used to compute the variation in surface electric field as a function of the source frequency. Figure 7 shows the variation in surface electric field when the orthogonal horizontal magnetic induction field is 700 gammas. The induced electric field is highly dependent on frequency. The flattening of the induced electric field at about 10^{-2} Hz corresponds to the maximum in the apparent resistivity at this frequency. A uniform earth model would not show this flattening, but only a continuous decrease in electric field magnitude with decreasing frequency.

V. THE L4 SYSTEM AND EARTH POTENTIAL OUTAGES

The L4 system consists of coaxial cables powered in pairs by power-feed stations. Normally, the maximum distance between power-feed stations is 242 km (150 miles), with a nominal repeater spacing of 2 miles. The power system is grounded at one end, and the output voltages of the four dc-to-dc converters (each rated to deliver 1800 V and a nominal line current of 520 mA) are balanced so that the voltage to ground at the "floating ground" end is zero. Figure 8 shows a typical L4 system powering section in the presence of an earth potential. In the presence of slowly varying voltages, the floating ground has a threshold of 370 V, above which it becomes automatically grounded. The automatic grounding feature serves as protection to the system. The floating ground must be restored to its normal condition manually.

Direct-current earth potentials produce changes in the L4 system line current that can cause transmission impairment and/or converter shutdown. The line current is unaffected by earth potentials until the 370 V threshold is exceeded. After grounding occurs at the floating point end, the earth potential appears in series with the metallic power-feed loops of both lines. The earth potential will increase the voltage on the line of the same polarity, causing an increase in that line current. The potential will decrease the voltage on the line with the opposing polarity, causing a decrease in that line current. Since earth potentials produced by geomagnetic variations frequently reverse polarity on rather short time scales, both lines will experience high and low currents. The magnitudes of the line currents are dependent on the following factors:

(*i*) Magnitudes of the earth potentials.
(*ii*) Degree of balance of the power system.
(*iii*) Dynamic resistance of the line and the converters.

System designers have analyzed an ideal model of the L4 system to estimate the line current variations as a function of earth potential. The results of this analysis with respect to converter shutdown on a standard 242-km power section are:[21,22]

(*i*) At ≈ 6.5 V/km, the line with the aiding earth potential will experience a high current shutdown.
(*ii*) At ≈ 8.9 V/km, the line with the opposing earth potential will experience a low current shutdown of both converters feeding the line (see Fig. 8).

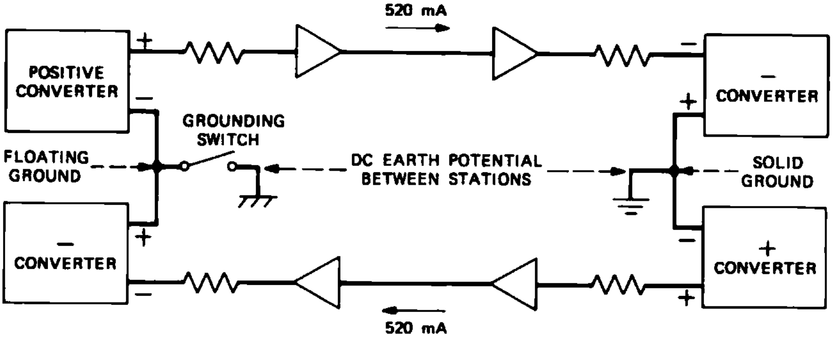

Fig. 8—L4 power-feed section in the presence of an earth potential.

The high current shutdown at ≈ 6.5 V/km is considered the most serious effect of earth potentials and, as is discussed below, is most likely the cause of the Plano-Cascade L4 shutdown of 4 August 1972.

The surface electric field induced along the Bell System L4 route from Plano to Cascade at approximately 2242 UT, 4 August 1972, can be determined from eq. (2). The magnetic field variation $|\Delta B/\Delta t|$ can be determined from Fig. 4 and the surface impedance can be determined from eq. (3) using the Plano earth resistivity model. The estimated geomagnetic disturbance of ≈ 700 γ/min (see Fig. 4) will induce a perpendicular surface electric field of ≈ 7.4 V/km (see Fig. 7).

The estimated direction of the geomagnetic disturbance vector was about 40° north of east (see Fig. 4), making an angle of approximately 70° with the Plano L4 route. For this angle, about 94 percent of the induced electric field, i.e., ≈ 7 V/km, would directly affect the L4 power-feed section. Bell Laboratories engineers have established a working shutdown value range for earth potentials of 6.5 V/km ±20 percent.[22] Comparison of this range to the ≈ 7 V/km value deduced for 4 August from magnetic field fluctuations shows that the surface electric fields that were most probably induced along the Plano to Cascade route at ≈ 2242 UT 4 August 1972 were probably sufficient to cause the L4 shutdown that took place.

The Uniqueness of the Plano L4 Outage

A complete explanation of why the Plano-Cascade section of the transcontinental L4 route experienced a shutdown and why other sections did not is not available at the present time. To establish some argument for uniqueness, it is worthwhile to outline some factors that might contribute to a telluric current shutdown. The major factors can be divided into geophysical conditions and system susceptibility.

Previous sections of this paper have dealt with the importance of the rate of change of the inducing field $|\Delta B/\Delta t|$ and of the surface impedance in determining the induced telluric currents. To achieve a maximum telluric current or earth surface potential along an L4 route, the horizontal magnetic field variation must be perpendicular to the direction of the route.

The contour maps shown in Fig. 4 illustrating the area distribution of $|\Delta B/\Delta t|$ and its direction angle in the interval 2241 to 2242 UT across North America are a valuable tool for determining the magnitude of the geomagnetic disturbances that actually affect an L4 power-feed section. As mentioned above, an estimated 94 percent of $|\Delta B/\Delta t|$ at 2242 UT affected the Plano-to-Cascade power-feed section. The L4 power sections immediately to the east of Plano and immediately to the west of Cascade both have a more east-west direction than the Plano-to-Cascade section. This means that only an estimated 60 percent of $|\Delta B/\Delta t|$, producing an electric field of ≈ 4.7 V/km, will affect these sections. This estimated electric field value is below the lower-limit system shutdown value of 5.2 V/km. These comments must be qualified by the fact that, as noted earlier, the available magnetometer data were certainly not optimum to determine field changes and directions with high accuracy.

The frequency response of the earth's surface impedance along the cable route is also a very important factor in producing maximum telluric currents. As shown in Fig. 7, the frequency response of the Plano earth model was a maximum at $\approx 10^{-2}$ Hz, which is the frequency of the largest magnetic variations at 2242 UT. Analytical results from various earth resistivity models have shown the frequency response of the surface impedance to be fairly sensitive to changes in layer thickness.[21] If the earth resistivity structure profile were known along the entire transcontinental L4 route, it would aid in the determination of which sections of the route are most susceptible to telluric currents. This information is not presently available, and probably will not be for quite some time. Thus, this discussion indicates that a combination of geophysical factors is needed to produce maximum telluric currents along a specified cable route. All these factors are very difficult to estimate at any particular time from the distribution of geomagnetic and telluric observatories presently existing in North America.

From the point of view of system susceptibility, each power-feed section of the L4 route will most likely have a different earth potential shutdown value. This condition exists because of variations in the power system balance, because of variations of dynamic resistance in the individual lines and convertors, and because of the length of any particular power-feed section. For instance, the Plano-to-Cascade L4 power-feed section, at $\approx$ 248 km, is the longest in the Bell System. The L4 sections immediately to the east and to the west are $\approx$ 213 and $\approx$ 230 km long, respectively. The decreased lengths in these sections increase the critical shutdown voltages to $\approx$ 7.4 and $\approx$ 6.8 V/km, respectively.

VI. SUMMARY

The preceding discussions, using most of the existing North American data available for the time period around the L4 system outage of 4 August 1972, have indicated that the geomagnetic disturbances were apparently sufficient to produce the outage on the Plano, Illinois, to Cascade, Iowa, route. The geomagnetic disturbances were produced primarily by large distortions of the earth's magnetosphere, whose boundary was observed to be pushed inward to an altitude of about four to five earth radii over North America at the time of the L4 outage. Therefore, the geomagnetic disturbances that produced the outage did not arise from enhanced auroral current systems that are normally associated with power system problems during magnetic storms.

It is difficult to establish the uniqueness of the L4 problem along the Plano-Cascade route during this large storm. A large part of this problem arises because of the insufficiency of the geophysical data, data concerning the magnitudes and spatial distributions of the magnetic fields and earth currents during the magnetic storm as well as data on the geological structure under the L4 route.

In addition to problems of coaxial system outages from large geomagnetic disturbances, it is likely that smaller magnetic storms may occasionally induce sufficient currents on some routes in certain locales to produce transmission impairments. Experimental work to study this problem is presently under way.

VII. ACKNOWLEDGMENTS

We thank our colleagues in the geophysical community for their discussions and help in supplying data for this study. In particular, we acknowledge profitable discussions with H. Fukunishi, D. J. Williams, and L. J. Cahill, and the assistance of J. N. Barfield, G. Jeans, and W. Paulishak of NOAA, Boulder, Colorado, in obtaining magnetograms. D. B. Ledley of NASA/Goddard kindly supplied the ATS-5 data. We thank S.-I. Akasofu and M. Buhler of the Geophysical Institute, University of Alaska, for digitizing the U. S. magnetograms that were readable. In particular, we thank G. J. Van Beek, P. Serson, and J. Walker of the Division of Geomagnetism, Earth Physics Branch, Department of Energy, Mines, and Resources in Ottawa for their generosity in supplying data from their array of digital magnetometer stations in Canada. We thank also the Illinois Geological Survey for their description of the Plano area geology. A special note of thanks goes to E. W. Geer and K. D. Tentarelli, Bell Laboratories, for their many helpful discussions on the operation of the L4 system.

REFERENCES

1. J. G. Roederer and A. H. Shapley, "Overall Summary of August 1972 Phenomena and Data," *Collected Data Reports on August 1972 Solar-Terrestrial Events*, Part I, H. E. Coffey, ed., Boulder, Colorado: U. S. Dept. Commerce, NOAA, July 1973, pp. 1–2.
2. M. Pomerantz and S. P. Duggal, "Record-breaking Cosmic Ray Storm stemming from Solar Activity in August 1972," Nature, *241*, February 2, 1973, pp. 331–332.
3. T. A. Croft, "Traveling Regions of High Solar Wind Density Observed in Early August 1972," J. Geophys. Res., *78*, June 1, 1973, pp. 3159–3166.
4. V. D. Albertson and J. A. Van Baelen, "Electric and Magnetic Fields at the Earth's Surface due to Auroral Currents," IEEE, *PAS-89*, 1969.
5. G. W. Longanecker and R. A. Hoffman, "S³-A Spacecraft and Experiment Description," J. Geophys. Res., *78*, August 1, 1973, pp. 4711–4718.
6. E. I. Loomer and G. J. van Beek, "The Development of Current Vortices in the Polar Cap Preceding the Large Magnetic Storms on August 4–5 and August 9, 1972," Collected Data Reports on August 1972 Solar-Terrestrial Events, Part III, H. E. Coffey, ed., Boulder, Colorado: U. S. Dept. Commerce, NOAA, July 1973, pp. 722–726.
7. D. B. Ledley, private communication.
8. W. D. Cummings and P. J. Coleman, Jr., "Magnetic Fields in the Magnetopause and Vicinity at Synchronous Altitude," J. Geophys. Res., *73*, September 1, 1968, pp. 5699–5718.
9. T. L. Skillman and M. Sugiura, "Magnetopause Crossings of the Geostationary Satellite ATS 5 at 6.6 R_E," J. Geophys. Res., *76*, January 1, 1971, pp. 44–50.
10. J. W. Freeman, Jr., C. S. Warren, and J. J. Maguire, "Plasma Flow Directions at the Magnetopause on January 13 and 14, 1967," J. Geophys. Res., *73*, September 1, 1968, pp. 5719–5732.
11. L. J. Lanzerotti, W. L. Brown, and C. S. Roberts, "Energetic Electrons at 6.6 R_E during the January 13–14, 1967, Geomagnetic Storm," J. Geophys. Res., *73*, September 1, 1968, pp. 5751–5760.
12. T. W. Lezniak and J. R. Winckler, "Structure of the Magnetopause at 6.6 R_E in Terms of 50- to 150-keV Electrons," J. Geophys. Res., *73*, September 1, 1968, pp. 5733–5742.
13. G. A. Paulikas, J. B. Blake, S. C. Freden, and S. S. Imamoto, "Boundary of Energetic Electrons during the January 13–14, 1967, Magnetic Storm," J. Geophys. Res., *73*, September 1, 1968, pp. 5743–5750.

14. D. J. Williams, private communications, 1973, 1974; L. J. Cahill, private communications, 1973, 1974.
15. T. Rikitake, *Electromagnetism and the Earth's Interior*, Amsterdam: Elsevier Publishing Company, 1966.
16. J. R. Wait, *Electromagnetic Waves in Stratified Media*, New York: Pergamon Press, 1962.
17. W. J. Peeples, *Magneto-telluric Profiling over a Deep Structure*, Ph.D. Thesis, University of Alberta, Edmonton, Alberta, 1969.
18. H. F. Morrison, *Magneto-telluric Profile Across the State of California*, Ph.D. Thesis, University of California, Berkeley, 1967.
19. T. Madden and P. Nelson, "A Defense of Cagnaird's Magneto-telluric Method," Geophysics Laboratory, MIT, Project NR-371-401, 1964.
20. Illinois Geological Survey, private communication.
21. C. W. Anderson, III, "Effects of the August 4, 1972, Magnetic Storm on Bell System Long-Haul Communication Routes," *Corrosion '74*, National Association of Corrosion Engineers, March 1974.
22. E. H. Angell and K. D. Tentarelli, private communications, 1973.
23. K. D. Tentarelli, private communication, 1974.