Studies of Large-Scale Earth Potentials Across Oceanic Distances

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This paper describes some ongoing research to characterize and understand the large-scale (on the order of several thousand kilometers) geoelectric potentials that can be induced within the Earth by fluctuations of the geomagnetic field. An understanding of these induced potentials can be important for carrying out some geophysical investigations, as well as for solving numerous engineering problems related to the design and deployment of long, conducting installations on the Earth's surface. Such installations include the systems used to power long-distance cables, electrical power distribution networks, and pipeline corrosion-control systems. The magnitude of the induced potentials fluctuates significantly in time and in spatial extent. It reflects both the highly variable nature of the Earth's space plasma environment that produces the geomagnetic fluctuations and the heterogeneous nature of the geological structure of the Earth's surface and upper mantle. Present-day models of Earth's magnetic fluctuations are insufficient to predict the geopotentials reliably, particularly the extreme geopotentials that might be experienced on a specific long route. Thus, such geopotential measurements as those described in this paper on AT&T cables in the Atlantic and Pacific Oceans can contribute important knowledge of the Earth's geophysical environment, as well as new geopotential information for engineering design.

Introduction

Solar emissions, including the visible photons that are so important for sustaining life, continually affect the Earth and the space around it.[1] In particular, the hot outer atmosphere above the sun's visible surface—called the *solar corona*—continually expands into the interplanetary medium in the form of an ionized gas, which is composed predominantly of protons and electrons. This ionized gas, known as the *solar wind*, has a density at Earth's orbit of about ten particles per cubic centimeter and a temperature of about 1 keV (equivalent to about 10^7 K). It interacts with the Earth's magnetic field, bounds it, and forms it into the shape of a comet (invisible to the eye), with a tail extending many hundreds of Earth radii away from the sun (Figure 1).

This comet-shaped region is called the *magnetosphere*. Its characteristics fluctuate over time, and its sunward boundary has a typical distance of about 65,000 km (or about ten Earth radii). Charged particles, again principally protons and electrons, are contained within the magnetosphere. These particles possess a wide range of energies; those having energies from several tens of keV to many MeV are confined by the Earth's magnetic field and form the Van Allen radiation belts.

Large-scale electrical currents flow continuously within the magnetosphere and ionosphere (the ionized gas region at the top of the atmosphere that begins at an altitude of about 100 km) because of the charged particles that exist in the space around Earth.
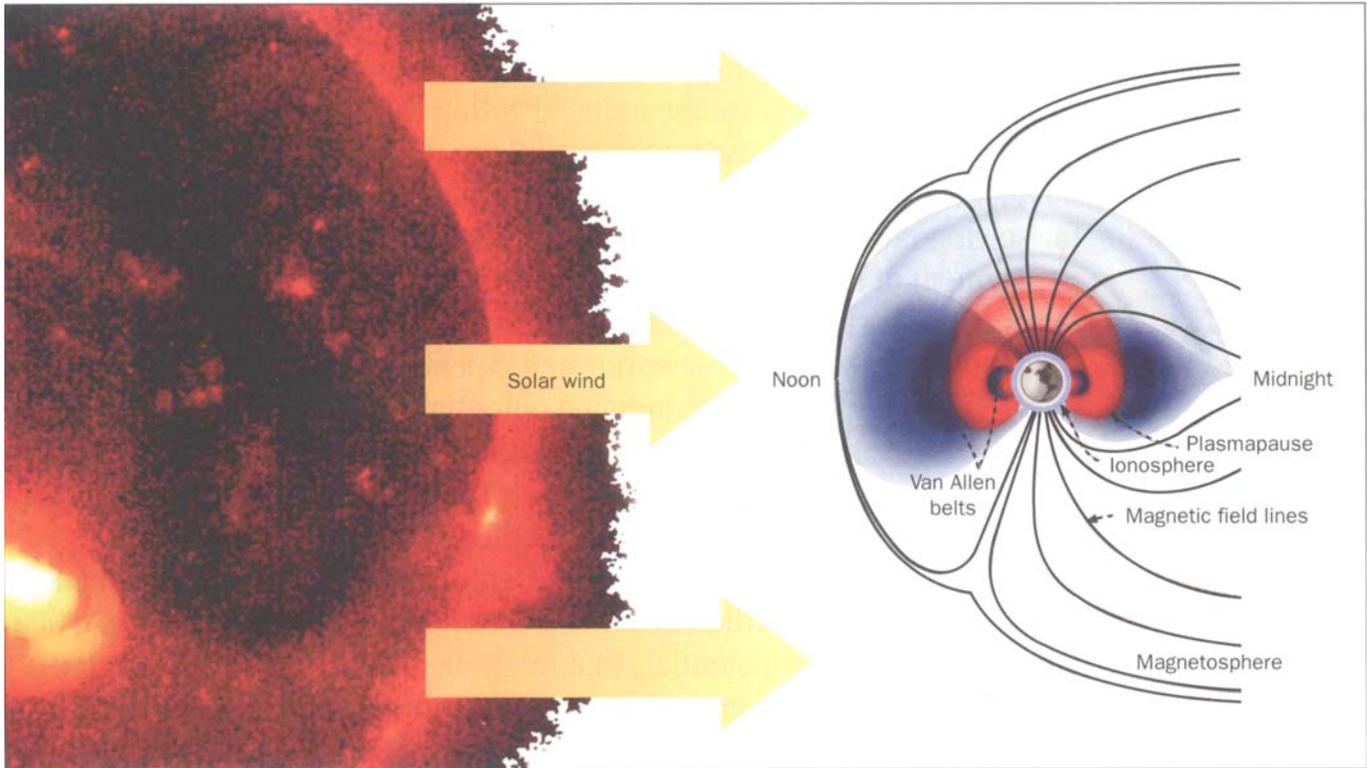
Figure 1. This rendering shows the sun, the Earth, and the space environment of the inner solar system. Emissions from the sun constantly affect the Earth and its surrounding space. The *solar corona*, shown here in an x-ray image of the sun made by the Japanese Yohkoh spacecraft on 26 November 1994, continually expands into the interplanetary medium as an ionized gas. This gas is known as the *solar wind*, and it interacts with the Earth's magnetic field, forming it into the shape of a comet. The tail extends many hundreds of Earth radii away from the sun.

The solar wind flow is not steady, being influenced by solar activity, such as sunspots and solar flares. The continual buffeting of the magnetosphere by the variable solar wind causes the electrical currents to vary with time scales ranging from milliseconds to millennia.

The time variations in these electrical-current systems produce changes in the background magnetic field on the Earth's surface. This is particularly important to long, conducting technical systems, such as oceanic cables. The changes in the magnetic field tend to be greater at higher geomagnetic latitudes (which, in general, do not coincide with geographic latitudes). These variations in the background magnetic field induce electrical currents to flow within the Earth because its surface and upper mantle consist of interspersed, often layered, conducting and insulating materials. The spatial heterogeneity of the Earth's conductivity can significantly affect the electrical potentials that can be induced across a given region by the time-varying geomagnetic field. The actual physical situation for inducing geopotentials across any given path is, *in toto*, a very complex phenomenon because the ionosphere and magnetosphere current systems are also heterogeneous with respect to the Earth's surface. Thus, a highly time-variable and spatially heterogeneous geomagnetic field induces a potential distribution across a highly heterogeneous Earth.

In addition to the generation of Earth potentials by time variations of the external geomagnetic field, the movement of ocean water (a good conductor) produces a potential drop from one coast to another. Ocean tides pro-

Table I. Examples of large-scale geopotentials across AT&T cables

Date	Route	Geopotential (V/km)
24 March 1940	Minneapolis, Minnesota to Fargo, North Dakota	2.0
11 February 1958	Clarenville, Newfoundland to Oban, Scotland	0.4
4 August 1972	Plano, Illinois to Cascade, Iowa	~7.0*
13 March 1989	Tuckerton, New Jersy to Widemouth, United Kingdom and Penmarc'h, France	0.12

*Inferred from PFE design parameters and geomagnetic field analysis

Panel 1. Abbreviations, Acronyms, and Terms
LT—local time
PFE—power feed equipment
UT—universal time

duce the largest such drops, having magnitudes that depend on the tidal characteristics relative to a cable route. While tides consist of many periodic components, the frequencies (and amplitudes) observed in cable voltages are occasionally quite different from those expected.

Earth Potentials

The history of the analysis of Earth potentials is long and fascinating. Studies were initiated during the mid nineteenth century with the installation of the original telegraph lines in the United States and Europe. The earliest installations, covering distances up to about 100 kilometers, experienced unexpected and continually changing potential drops that seriously affected their operation. At times, during major disturbances of the Earth's magnetic environment, the battery power supplies for the telegraph lines became disabled. For example, during one hours-long interval in 1859, telegraph lines running from Boston to points north and south alternately operated without batteries and not at all, depending on the direction of the induced Earth potentials.

At that time, the cause of such effects was not understood. During the mid twentieth century, however, the relationship of the Earth's potentials to fluctuations of its magnetic field began to be clarified. Understanding of the Earth's space environment increased dramatically in the latter third of the century with the advent of the space age. Thus, understanding of the relationships of the electrical currents in the space around the Earth to potentials on its surface also increased. Nevertheless, the magnitudes of earth potentials that might occur across any specific power line or cable route in a specific interval of time cannot be determined or modeled at present from first principles.

Induced earth potentials must be considered in designing long, conducting technological systems, such as power feed equipment (PFE) for oceanic cables.[2] The reason for this is that such potentials can still disrupt power and cable systems and even damage them. For example, the powering system of an AT&T L4 cable running from Plano, Illinois, to Cascade, Iowa, was disrupted by massive earth potentials in 1972,[3] and the entire province of Quebec suffered a power disruption for many hours during an interval of great geomagnetic disturbance in 1989.[4] This same disturbance induced large earth currents to flow through multimillion-dollar transformers at a nuclear power plant in southern New Jersey, causing them to burn out. A peculiar aspect of managing such problems is that these disturbances tend to occur near the peak of the solar cycle (about 11 years) so that individuals familiar with such effects have often been
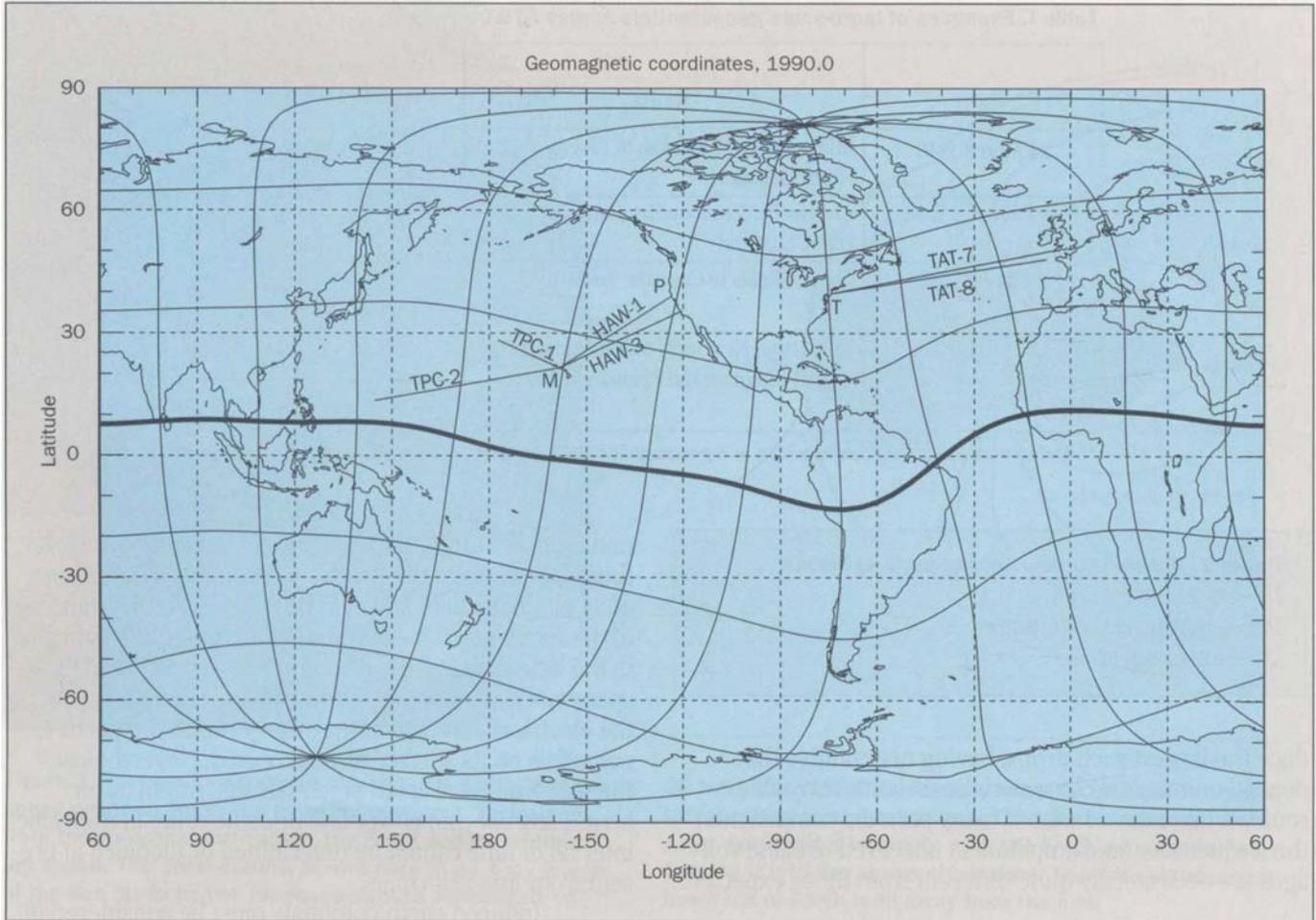
Figure 2. This drawing, in which the solid lines form geomagnetic latitude and longitude references, shows the locations of the AT&T transoceanic cables presently instrumented for measuring the Earth's large-scale geopotential. All cables illustrated except TAT-8 are decommissioned, and their routes approximate those of other in-service or planned cables.

reassigned before the next major disturbance cycle.

Statistical studies of Earth potentials along existing routes provide information important to engineering factors. For example, it might be feasible—from an engineering perspective—to design all PFE to withstand the highest potential ever observed in the past (see Table I). Such an approach may be prohibitively expensive, however, particularly for routes on which high potentials are unlikely. Statistical studies can aid in this type of determination.

In addition to their intrinsic engineering interest, studies of large-scale geopotentials can also provide new information about the geophysical environment of the Earth. Generally, financial feasibility precludes the installation of long conductor spans, such as transoceanic cables, purely for scientific research. Existing long-haul AT&T undersea cables, however, provide a unique research opportunity.

Instrumented Cable Routes

Figure 2 illustrates the transoceanic cables currently instrumented for measuring the geopotential. Previously, other AT&T cables—including TAT-6 and, dur-

ing its initial lay, TAT-7—were monitored for short intervals. All the cables illustrated in Figure 2 except TAT-8 are decommissioned. The decommissioned cable systems approximately follow the routes of in-service or planned cables. Experience with the two parallel HAW-1 cables shows that geopotential measurements will closely track actual conditions on geographically proximate in-service systems. Thus, the decommissioned cables can provide "clean" measurements of the induced voltages without having to compensate for such factors as the temperature sensitivity of power-supply voltages.

These cable routes are shown with superimposed geomagnetic coordinates (the solid grid lines in Figure 2; the geomagnetic equator is the heaviest of the solid lines). As noted earlier, the geomagnetic latitude can be an important parameter in determining the intensity of disturbances that can affect long, conducting cable systems. Studies of the geopotential at different geomagnetic latitudes can provide crucial information—for example, the compensation level for the Earth potential that must be included in the design of PFE at different locations.

Figure 2 also shows that the trans-Pacific cables are located at relatively low geomagnetic latitudes compared to the two cables presently being monitored in the Atlantic Ocean. This difference in latitude results partially from the angular tilt of the Earth's magnetic dipole axis with respect to its rotational axis. The tilt is biased toward the east coast of North America, as shown in the illustration.

Special AT&T computer-based instruments are installed at the AT&T cable stations in Tuckerton, New Jersey (T), Point Arena, California (P), and Makaha, Hawaii (M). The instruments continuously monitor cable voltage relative to the local ground, digitize the values at two-second intervals, and write the data to hard-disk cassettes. The instrumentation at Tuckerton monitors both the decommissioned TAT-7 and the in-service TAT-8 cables. In the case of TAT-8, the PFE voltage and current-monitor outputs are recorded. The measured PFE voltage variations correspond to the inverse of the induced voltages across the cable because the PFE uses a highly regulated constant current supply. At Point Arena, the two HAW-1 cables are monitored. The remaining Pacific cables illustrated in Figure 2 are monitored at Makaha.

At Tuckerton, TAT-8 uses the station's ocean ground; TAT-7 uses a separate ocean ground from the first

offshore repeater housing. A specially installed telecommunication-type ground electrode is used at Point Arena (an iron rod, 1.5 m long, covered by a 20-cm-diameter layer of coke dust). The station's ocean ground is currently used at Makaha.

In addition to the cable-monitoring instruments, a three-axis fluxgate magnetometer is installed outside each cable station to provide continuous measurements of the local Earth's magnetic-field conditions. The instrumentation acquires and records these data simultaneously, together with accurate time information.

Global Geopotentials

The geopotential as recorded across the various cable routes varies with time of day and season, as well as with the level of geomagnetic activity. Examples of these potentials on two different days are shown in Figures 3 and 4 to provide some perspective on the variations that can be observed.

The interval of 13-14 March 1989, which occurred during the most recent period of maximum sunspot activity (1989-1991), was one of particular geophysical interest because of its effects on power systems. It was during this interval that electrical power was disrupted in Quebec.[4] The upper tracings in Figure 3 show the variations in the trans-Atlantic geopotential as measured in variations of the TAT-8 PFE and the west-east component of the Earth's magnetic field. Both the trans-Atlantic geopotential variations and west-east magnetic-field component were recorded at the Tuckerton cable station during the 24-hour interval centered on midnight, universal time, 13 March.[5] Local time (LT) at Tuckerton is five hours later than universal time (UT); LT = UT - 5 hours. The lower tracings in Figure 3 show the same two physical variables on an expanded time scale, a six-hour interval again centered around midnight UT on 13 March.

Two time intervals occurred during this massive geomagnetic disturbance when the true (corrected for changes in the current supply) peak-to-peak voltage excursion was measured to change by more than 700 V within a few minutes. At about 2148UT on 13 March, the true rate of change of the geopotential drop was approximately 300 to 450 V/min. This corresponded to a rate of change in the west-east magnetic field at Tuckerton of approximately 300 nT/min., about one-third of that observed at the time of the 1972 outage of the continental
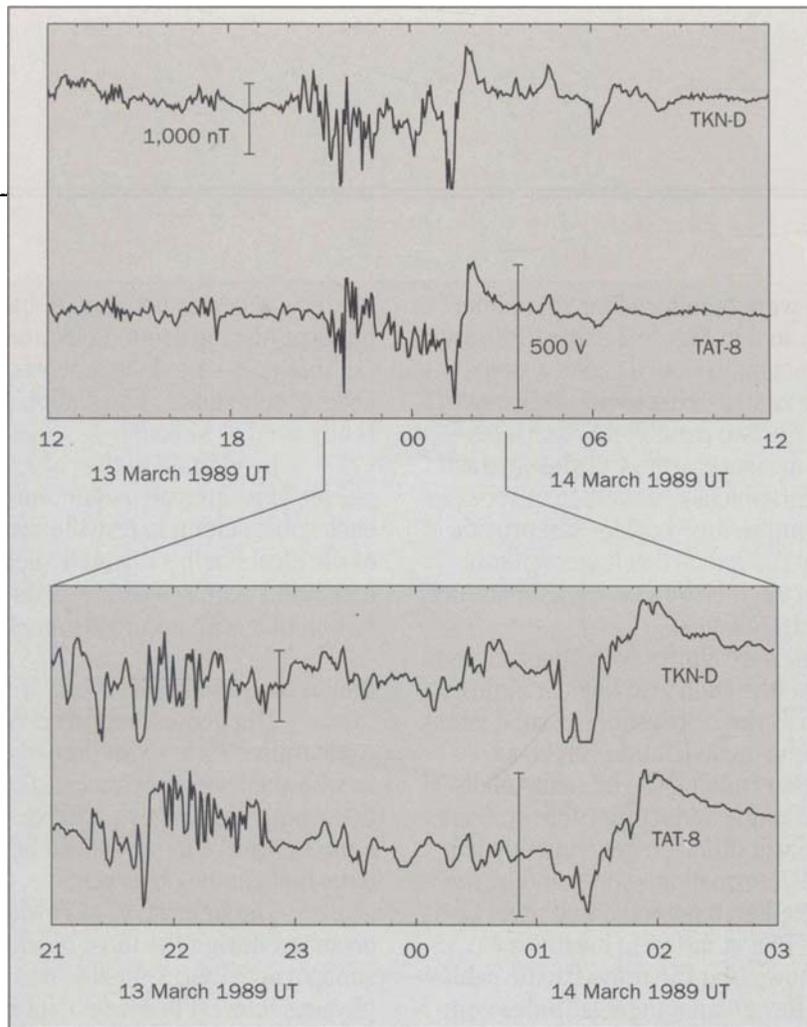
Figure 3. These tracings represent time variations of the geopotentials measured across the Atlantic Ocean using the in-service TAT-8 cable during a large geomagnetic disturbance. The west-east geomagnetic field variations as measured at the Tuckerton, New Jersey cable station are also shown. The lower segment is a higher time resolution of the central six hours of data shown in the one-day plot at the top.

L-4 cable.[3] At about 0115UT on 14 March, the true rate of change of the cross-Atlantic potential drop was on the order of 37 V/min.

The geopotential measurements for 26 November 1994, made on all the cables shown in Figure 2, are recorded in Figure 4. The data traces are arranged east to west, top to bottom, with the Atlantic cables in the upper two traces and the most western Pacific cables (TPC-1 and 2) in the lowest two. The variations in the TAT-8 constant-current PFE are shown by the dashed trace. The traces in color show the west-east components of the Earth's magnetic field as measured at the three cable stations, again arranged vertically by their location, east to west. Local noon and local midnight at the center of each cable and at the cable stations (in the case of the magnetometer traces) are indicated, respectively, by the open

and closed diamonds. Each solid amplitude bar appearing perpendicular to the cable-voltage tracings corresponds to 3 V per 1,000 km.

Figure 4 depicts the following features:
- The principal interval of the disturbances in both the geomagnetic field and geopotential occur approximately coincidentally in UT over most of the northern hemisphere spanned by the cables. The sizable negative decreases in the geopotential, at around hour 11 UT, were measured along all cable routes.
- The peak-to-peak amplitudes of the voltage variations—not as great as those appearing in the interval shown in Figure 3—have an overall envelope that is larger at lower latitudes rather than at higher latitudes prior to 12 UT. This is contrary to common experience, where greater geomagnetic activity tends to occur at higher
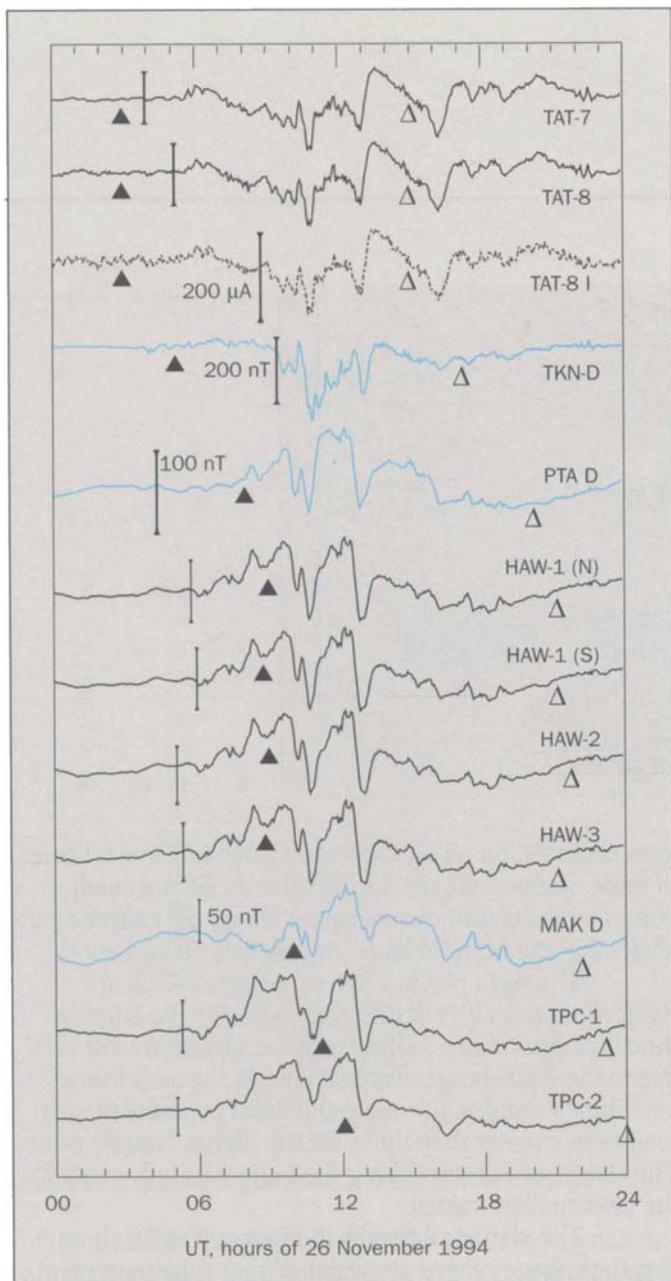
latitudes. The geopotential changes measured in the Atlantic Ocean, after about 12 UT, are not as evident in the Pacific Ocean.

- A reasonably good qualitative correspondence can be seen between the magnetometer variations and those appearing in the cable voltages.

The fact that all the cables showed disturbances in approximately the same UT interval is surprising given the wide range in LT coverage. In general, the largest geomagnetic disturbances (substorms) occur near local midnight and often exhibit minor or even no effects near local noon. Enhancements in the trapped particle fluxes circling the Earth (the "ring current") could produce more global geomagnetic effects. At this time, however, the level of activity

was not as great as that required to produce a significantly enhanced ring current.

The 26 November interval of geomagnetic disturbance was triggered by the passage of a solar coronal-hole boundary over the magnetosphere. This boundary separated magnetic fields in the solar equatorial plane from those in the polar regions (corresponding to the boundaries between the bright and dark regions, respectively, in the solar picture of Figure 1). These boundaries separate relatively strong solar wind (on the order of 700 km/s) in the sun's polar regions from relatively moderate wind (on the order of 400 km/s) in the near-equatorial plane. Qualitatively, it appears that the geomagnetic activity stimulated by this solar coronal-hole interaction with the magnetosphere produced a disturbance more global in scope than those often caused by other types of solar-wind variations.

Geopotential Distributions

Statistical studies of the potentials observed across the several monitored cables provide information on the ranges of the geopotential excursions that might be expected during different portions of the solar cycle and at various Earth locations. The results of some of these studies are presented in this section. They represent several months' data collected during both solar-minimum and solar-maximum conditions.
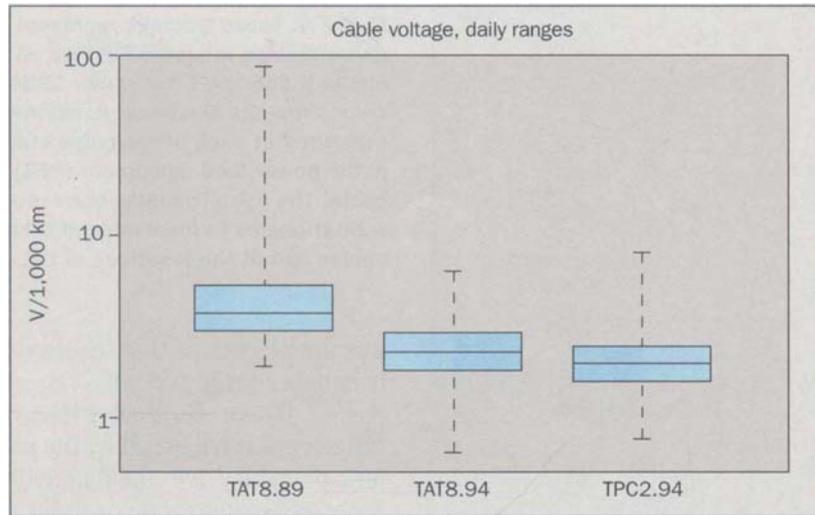
Boxplot statistics for the daily ranges of the geopotentials, in volts per 1,000 km, on TAT-8 for solar maximum (176 days between day 69 and day 277 in 1989) and solar minimum (180 days between day 175 and day 356 in 1994) are shown in Figure 5. The boxplot for the TPC-2 geopotential ranges is for data during the 1994 solar minimum (162 days between day 219 in 1994 and day 18 in 1995). The heights of the individual boxes correspond to the central 50 percent of the total ranges. In each case, the

Figure 5. This illustration shows the statistical distributions of the geopotential variations measured across TAT-8 during several months in 1989 (near solar maximum) and 1994 (near solar minimum), as well as across TPC-2 during the same months in 1994. The center line across each box represents the median value.

lines drawn across the boxes represent the medians. Both the upper and lower 25 percent of the ranges are shown by the dashed lines above and below the boxes, respectively.

Figure 5 shows that the median of the geopotential ranges for the same cable, TAT-8, is greater by at least a factor of two during solar-maximum conditions. In addition, the central 50 percent of the ranges, as well as the upper 25 percent, are considerably wider during solar maximum than solar minimum.

The two right-most boxes in Figure 5 compare solar-minimum geopotential ranges for two cables at different geomagnetic latitudes. The median range is greater for the higher latitude TAT-8 cable, as is the central 50 percent of the ranges. The upper 25 percent of the ranges, however, is found to be greater for the cable route closer to the geomagnetic equator.

The upper limit of the topmost 25 percent of the ranges in the TAT-8 solar-maximum boxplot results from the large variations on the two March 1989 days illustrated in Figure 3. This phenomenon is shown by the left plot in Figure 6, in which the solar-maximum and solar-minimum ranges from TAT-8 are ordered according to their amplitudes. The diagonal solid line across the lower quadrant represents equal values of the two variables. This plot clearly shows that the solar-maximum values are always greater than those for solar minimum and that there were two exceptionally high daily values. These two daily values were measured in March 1989, about 0.12 V/km on each of the two days. Three other very high volt-
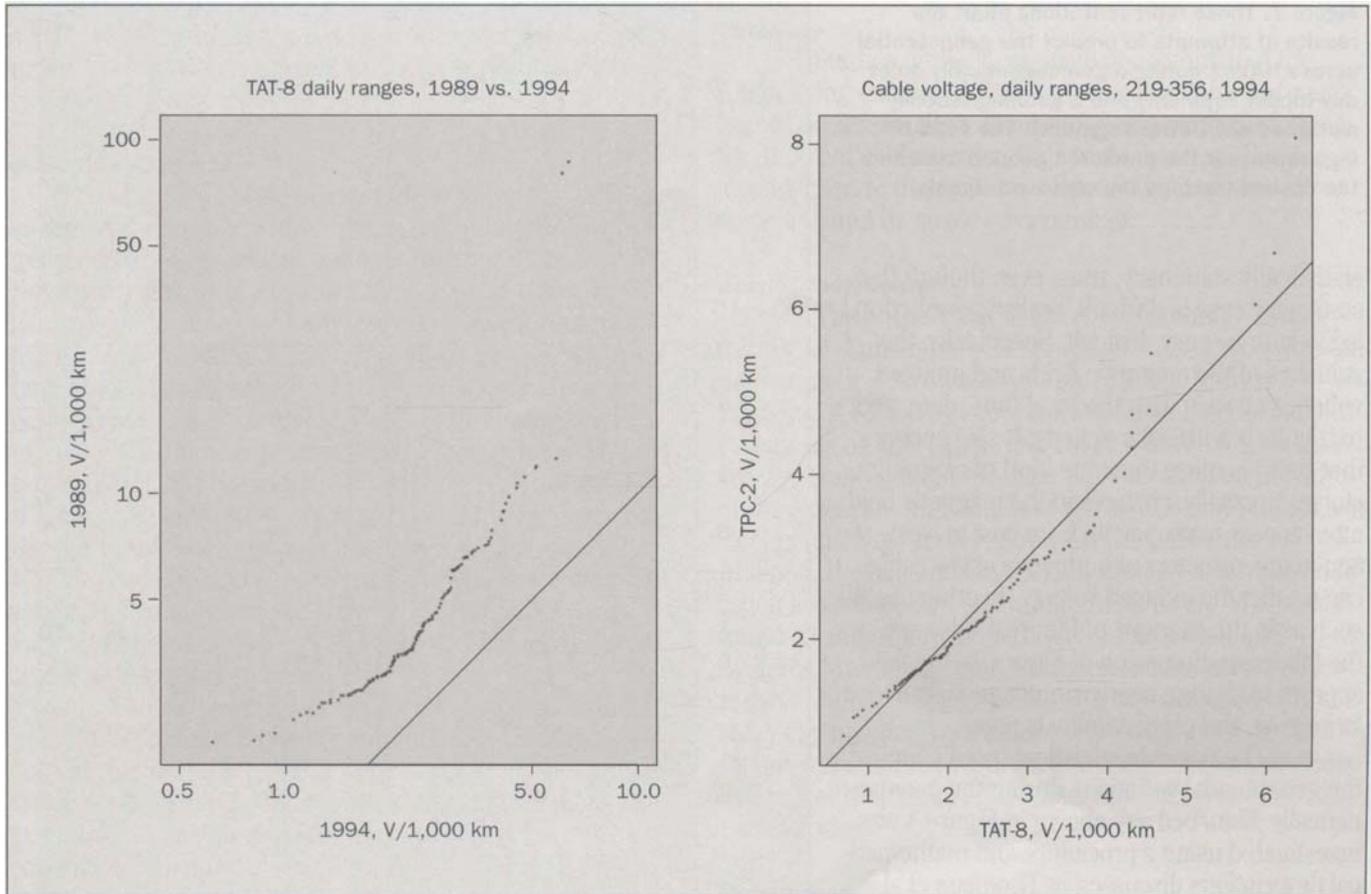
ages observed on AT&T cables are listed in Table I. Each of these events occurred during solar-maximum conditions, and the distribution of values shows the extreme variability that can occur in large geomagnetic disturbances.

The right plot in Figure 6 compares voltage ranges for two cables at different geomagnetic latitudes, but at the same times. Three regions appear to exist relative to the equal-range diagonal line. At the very lowest and highest ranges, the near-equatorial potential ranges tend to be greater than those for the higher latitude route. The ranges are greater along the higher latitude route for the intermediate values.

The statistical results in Figures 5 and 6 show that the voltage ranges are wider during solar-maximum conditions, which is expected because geomagnetic activity tends to be greater then. At first, however, the solar-minimum result showing wider ranges near the geomagnetic equator is surprising. This result could arise from the fact that the TPC-2 route is close to the location of the "focus" of the solar-induced day-side ionospheric current system (called the Sq, for solar-quiet system). Hence, this current system in the ionosphere could be an important factor in inducing geopotentials in the Earth near the geomagnetic equator, and it may be particularly important during solar minimum for the induced potentials.

Geopotential Predictability

Two of the more important objectives in studying induced voltages on undersea cables are the investigation

TAT-8 daily ranges, 1989 vs. 1994

Cable voltage, daily ranges, 219-356, 1994

Figure 6. The left segment compares the distribution of geopotential values across TAT-8 during solar-minimum (1994) and solar-maximum (1989) conditions. The right segment compares the distribution of geopotential values across TAT-8 and TPC-2 during solar-minimum conditions.

of the possible "predictability" of the observed signals and phenomena, and simultaneously, a greater understanding about the mathematics of predicting nonstationary processes. In the context of the research described in this paper, this latter objective would be the study of the predictability of the time and amplitude variations in the geopotentials as measured across a specific cable route. An investigation of the predictability of a geophysical parameter, such as the geopotential, can take many forms. These range from detailed modeling of all the physical steps that might cause the final phenomena (perhaps even beginning with inputs as distant as the sun) to the pragmatic use of experience with a limited set of measurements to predict, on the basis of statistical analysis, the future values of the geopotential.

In theory, methods to predict future values of stationary processes (those in which statistics are indepen-

dent of time) from previous measurements have been known since the work of Wiener and Kolmogorov in the 1940s.[6] In practice, however, the cable environment still makes even these methods difficult, and detailed statistical analysis often provides results contrary to simple intuition. As an example, voltages induced on cables terminating at Tuckerton seem to be primarily coherent with changes in the east-west magnetic field, not the north-south component.[7]

More realistically, one must acknowledge that the geomagnetic environment (like many others) is not

Figure 7. These representations chart the results of attempts to predict the geopotential across HAW-1 during a geomagnetically quiet day (upper segment) and a geomagnetically disturbed day (lower segment). The solid tracings represent the predicted geopotential and the dashed tracings the observed signals.

statistically stationary; thus, even though the stationary case is difficult, realistic prediction is likely to be very difficult. Specifically, the statistics of the magnetic fields and induced voltages all vary with the local time, date, and particularly with solar activity. It also appears that there is more than one kind of magnetic storm. Normally, changes in the magnetic field often appear to propagate from east to west, and magnetometers at both ends of the cable can predict the induced voltage. In other cases, such as in the example of Figure 4 (also see the following discussion of Figure 7), the field appears to change nearly simultaneously over a large area, and predictability is poor.

The possible statistical "prediction" of the geopotential variations during the geomagnetically disturbed day shown in Figure 4 was investigated using a procedure and mathematical descriptions discussed in Thomson et al.[8] The invoked analysis techniques appeared able to extract a tsunami-induced voltage change on the HAW-1 cable from the background of geomagnetic signals.

Following the outline in the tsunami study, transfer functions were calculated between the geopotentials measured across the HAW-1 route and the geomagnetic field measurements made at both Point Arena and Makaha.[8] The transfer functions were estimated using nine approximately exponentially spaced time steps in the time domain that extended to one hour in the past from each given point. The ten days of data collected during the period 17 to 27 November 1994 were used to determine the transfer functions.

Some results of this procedure are shown in Figure 7. The solid tracing in each graph represents the predicted geopotential on HAW-1. The dashed tracings represent the observed signals. The top half of Figure 7,
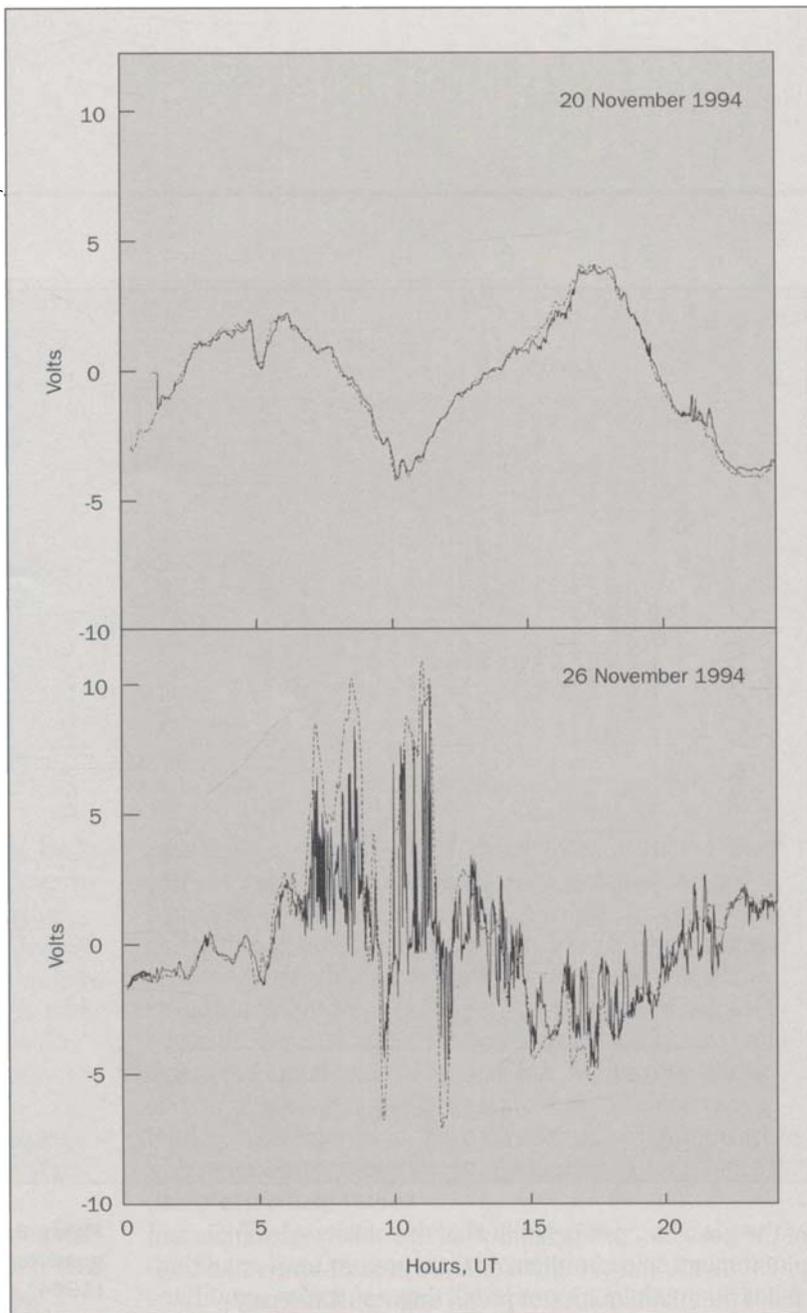
which represents the geomagnetically quiet day of 20 November 1994, shows that the set of transfer functions and the analysis procedure can effectively describe the observed geopotential signal. The situation for the geomagnetically disturbed day of 26 November 1994, however, is not as favorable.

The solid tracing in the bottom half of Figure 7 shows that the predicted signal has a much faster time variability than does the actual measured geopotential signal. While some of the larger excursions in the geopotential are nearly recovered by the prediction, the ability to catch the largest excursions is not very satisfactory over-

all. This result effectively demonstrates that substantially more investigation is needed to obtain predictive capability for these geopotentials.

Scientific Analyses

The data obtained from these geopotential measurements also contribute to understanding the Earth's geophysical environment. One interesting discovery was the similar response of cables over a broad range in UT to a magnetic disturbance (Figure 4). Another interesting discovery resulted from an analysis of the geopotentials on the two parallel HAW-1 cables, which are separated by about 75 km in the Pacific Ocean. The two cables effectively form a large, elongated Faraday loop. The net potential around the loop is induced only by the variations in the component of the geomagnetic field perpendicular to the current loop. Measurements showed that this large cable loop is much more sensitive than a magnetometer to magnetic-field fluctuations.[9] Thus, small variations in ionosphere currents could be derived from these measurements.

Some theoretical analysis has suggested that poloidal electrical currents from the toroidal magnetic field at the boundary of the Earth's core and lower mantle can leak through the mantle to the surface. Only the poloidal and not the toroidal magnetic field from the geomagnetic dynamo can be measured at the Earth's surface. Thus, a measurement of the "leaked" electrical current might provide information on the unmeasurable magnetic field.

Measurements from two of the decommissioned cables have been used in an attempt to place an upper limit on the steady-state (dc) geopotential on the Earth's surface. By using a time interval of many months, accurate statistics can be obtained on this geopotential value as the time variations from geomagnetic effects and ocean tides are averaged out.

Using HAW-1 data, the dc geopotential was found to be 0.183 ±0.056 mV/km during intervals of geomagnetic quiet.[10] If this value is interpreted in the context of theoretical discussions, then the result would imply that the value of the toroidal magnetic field at the core-mantle boundary within the Earth is about the same order of magnitude as the poloidal magnetic field extrapolated from the value measured at the surface. Such a conclusion can place limits on some models of the geomagnetic dynamo.

Summary

Studies of the large-scale geopotential of the Earth using existing AT&T transoceanic cables provide important information about PFE design considerations for different cable routes. Data from these studies can also be used to deduce new scientific information about the Earth and its space environment.

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