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Solar-Geophysical Effects on Northern and Mid-Latitude ELF Propagation

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The ionospheric phenomena that have the greatest effect on ELF propagation occur at middle to northern latitudes under conditions of path darkness. Polar cap events cause increased ion densities in the polar lower D region; these events can lead to greatly increased absorption on northern latitude paths. Under nighttime conditions, precipitated electrons can affect transmitting and receiving stations in the auroral zone by enhancing the conductivity of the lower E region. Precipitation of charged particles trapped in the outer radiation belt can affect stations and paths at even lower latitudes.

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Examples of ELF propagation data under disturbed conditions are rare, but the few that have been recorded in recent years show significant correlation with solar proton flux emissions, galactic cosmic ray fluctuations, auroral and polar cap absorption events, and geomagnetic storms. These correlations permit a preliminary, qualitative confirmation of the effects that solar charged particle emissions were expected to have on ELF propagation.

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CONTENTS

SOLAR-GEOPHYSICAL EFFECTS ON NORTHERN AND MID-LATITUDE ELF PROPAGATION

INTRODUCTION

The purpose of this report is threefold: (a) to describe the types of ionospheric phenomena that may be expected to affect propagation of ELF waves in the earth-ionosphere waveguide, (b) to anticipate from the basis of existing theory and from the small amount of measurement data on ELF transmissions the impact these phenomena may have on ELF communications, and (c) to present examples of ELF propagation measurements in which ionospheric effects are manifest. An earlier report (1) contained a review of theoretical and experimental investigations of ELF propagation that had been conducted prior to the availability of coherent, controllable sources of wave energy in the ELF band. It was the objective of that earlier work to suggest the areas of investigation that merited further study so that the likely effects of geophysical phenomena on communications in this frequency band could be assessed.

Due to the technical difficulties of radiating energy in the ELF band at high enough power to be detected at ranges of thousands of kilometers, very little data for this type of transmission have been gathered until quite recently. Dunn et al. (2) and Kuhnle and Smith (3) used a rented 67-mile section of power transmission line on the California-Nevada border (oriented roughly in an east-west direction), grounded at both ends, to radiate a 400-Hz continuous wave at 300 kw input power. Measurements on an easterly path were made in Utah (500-km range), Michigan (3000-km range), and New York (4000-km range). Both nighttime and daytime path conditions, as well as the sunrise transition period, were investigated. The measured attenuation constants were 3 to 3.5 dB/1000 km for nighttime propagation and 7.8 to 9.0 dB/1000 km for daytime propagation. There was evidence that during the night-day transition period a smooth transition from the usual nighttime received-signal level to the daytime value did not occur, but that the signal experienced rather deep fading (as much as 20 dB) for a while, followed by recovery to the usual daytime level. This behavior may indicate that the ionospheric twilight zone causes a modal interference effect in ELF wave fields below the transition region, or may indicate the appearance of a transient, absorbing C layer during sunrise.

Ginsberg (4) used a transmitter and a 176-km horizontal antenna in North Carolina to radiate cw signals at 78 and 156 Hz. These signals were received at points on a single great circle path through Point Au Feu, New York (1139-km range), and Goose Bay, Labrador (2422-km range), to Keflavik, Iceland (4882-km range). This investigation yielded average attenuation rates at 78 Hz of 1.27 dB/1000 km for sunlit paths and 1.01 dB/1000 km for dark paths.

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The most recent work is reported by White and Willim (5) and Bannister (6). These workers, in an attempt to measure the average attenuation rates and phase velocities for ELF waves in the 40-to-50- and 70-to-80-Hz frequency bands made use of a low-radiated-power transmitter located in Wisconsin; signals were received in Maine, Connecticut, Utah, Nova Scotia, Alaska, Hawaii, Greenland, Norway, Greece, Saipan and the U.S. Virgin Islands, for several days at a time, over a period of more than two years. Because of the low radiated power at the transmitter, coherent integration times of hours were necessary, together with postprocessing averaging of days and weeks of data, to yield results of the required precision. Consequently, the effects of propagation-path variability due to geophysical effects, which are the subject of later sections of this paper, were not investigated. The methods developed in this measurement program are the backbone for the procedures used in succeeding ELF-propagation research programs. The description of these methods in the *IEEE Transactions on Communications* Special Issue on ELF (7) is highly recommended for interested readers. Figure 1 (Bannister, private communication, 1974) is a plot of the attenuation rates measured by Bannister and by White and Willim (normalized to 45 and 75 Hz), together with those of Ginsberg (4), Dunn et al. (2), and Kuhnle and Smith (3), for both nighttime and daytime conditions on the propagation path.

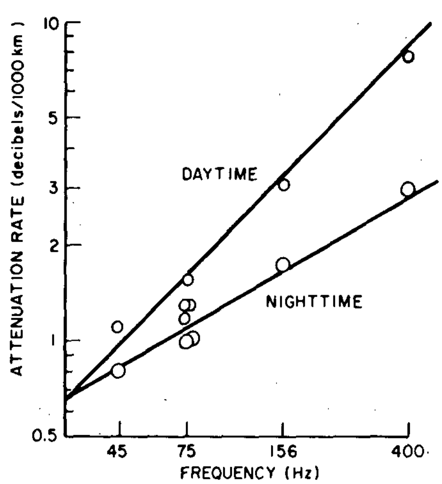

Fig. 1 — Attenuation rates in the ELF band measured from cw transmissions

Davis (8) has described the possible irregularities and anisotropies of propagation that may be important for ELF communications. Prominent among these effects are those which are peculiar to northern latitudes, where impulsive variations in the lower ionosphere occur as a consequence of the impingement of energetic particle fluxes from the sun.

These northern latitude phenomena are of particular importance because of the large number of likely ELF communications paths that pass through the auroral zone and polar cap. Figure 2 is a great-circle map centered in Wisconsin near the location of the ELF transmitter which has been used for recent and continuing propagation measurements. The 20% and 100% auroral contours are included as indications of the region over which the northern latitude phenomena to be considered in this paper are important. It should be evident that paths to the Mediterranean pass through a considerable portion of the auroral zone, paths to the Norwegian Sea and much of the North Atlantic pass through both the auroral zone and polar cap, and receiving sites in these locations and in northern Europe fall within regions affected locally by auroral activity. The charged-particle precipitation effects that influence the ionosphere in these regions are discussed briefly in the following section of this report, "Northern Latitude Phenomena." Means for discerning the influence of northern latitude effects on ELF propagation paths are treated under "Diagnostic Tools." Examples of suspected ionospheric variation effects on actual ELF signal measurements are treated under "Measurement Results."

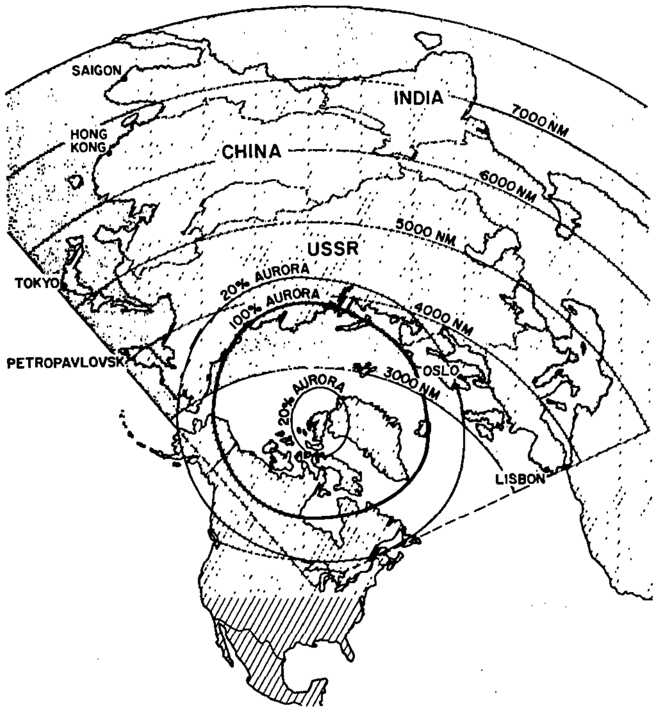

Fig. 2 — Relationship of the Wisconsin ELF transmitter to northern latitude propagation paths. The transmitter is located at the apex of the sector

NORTHERN LATITUDE PHENOMENA

The matter for consideration here involves ELF waves emitted by a subauroral-latitude transmitter, with an observer located on a path that crosses portions of both the auroral zone and polar cap and terminates at a receiver site which is itself within the auroral zone. Under these circumstances the task of discerning and diagnosing the effects of geophysical phenomena upon the ELF transmission is formidable. For the purposes of this paper we cannot take account of such short-term ionospheric disturbances as those caused by solar X-ray emissions (useful signal integration times are at present too long to permit these effects to be observed); even so, the influences of charged particles emitted by the sun and transported to the vicinity of the earth are themselves diverse enough to pose a difficult diagnostic problem.

The most pronounced ionospheric disruption associated with solar activity is, of course, a polar cap event (PCE), which occurs a number of hours after a solar eruption upon the arrival of large quantities of moderate-energy (1- to 100-MeV) protons in the vicinity of the earth. Figure 3 is a map showing an ELF propagation path from Wisconsin to Norway, a ring indicating the geomagnetic latitude of 60°; a cross-hatched area within the ring delineates the southern limit of access to the earth for protons in the 1-to-10-MeV energy interval under midnight conditions at midpath. The amount of the propagation path affected by protons incident on the polar cap is readily seen to be considerable, because the lower ionosphere in essentially all of the region north of this boundary will be disturbed.

Figure 4 contains a graphical summary of the characteristics of typical PCE's. Figure 4 (a) shows the variation of ionospheric stopping altitude for 1-to-100-MeV protons. Figure 4 (b) shows a typical proton integral energy spectrum for a PCE (9) and indicates that most of the proton flux is concentrated in the 1-to-10-MeV energy range. As Fig. 4 (c) indicates (10), the greater ionization efficiency of higher energy protons, which penetrate to lower altitudes, causes ionization production to peak at about 40 km altitude. Uncertainties in D-region chemistry make it difficult to translate these production rates into ion and electron density profiles, especially for nighttime; however, Fig. 4 (d) contains a comparison of normal nighttime ion density (10,11) with an estimate of a disturbed profile which probably represents a lower bound to the actual nighttime ion density. To obtain this curve, a small fraction of the normal nighttime ratio of negative ion to electron density (12,13) was applied to measured values of nighttime PCE electron density (10). The principal point conveyed by Fig. 4 is that PCE's affect the very lowest region of the ionosphere and give rise to several orders of magnitude enhancement of ion density at height around 40 km. ELF waves travelling in a portion of the ionosphere disturbed by a PCE can thus be expected to undergo significant absorption in excess of the normal low nighttime rate. Under daytime conditions, the influence of a PCE on an ELF path is probably much less, although still serious. Ion densities are lowered relative to nighttime PCE conditions by photo-detachment and associative detachment, resulting in somewhat reduced absorption. Field (14) indicates that daytime attenuation rates in the 40-to-80-Hz band may be raised by about 1 dB/1000 km over normal during a PCE. For both day- and nighttime cases, the main cause of attenuation is absorption due to ions below about 50 km.

A second ionospheric phenomenon associated with solar activity is that which stems from electrons in the 1-to-100-keV energy range precipitated into the auroral oval. Figure 5 is a map showing the Wisconsin-Norway ELF propagation path and the auroral oval at receiver site at midnight, which is the time at which ELF propagation effects will probably be worst for such a path. Auroral-zone effects are relatively unimportant along this

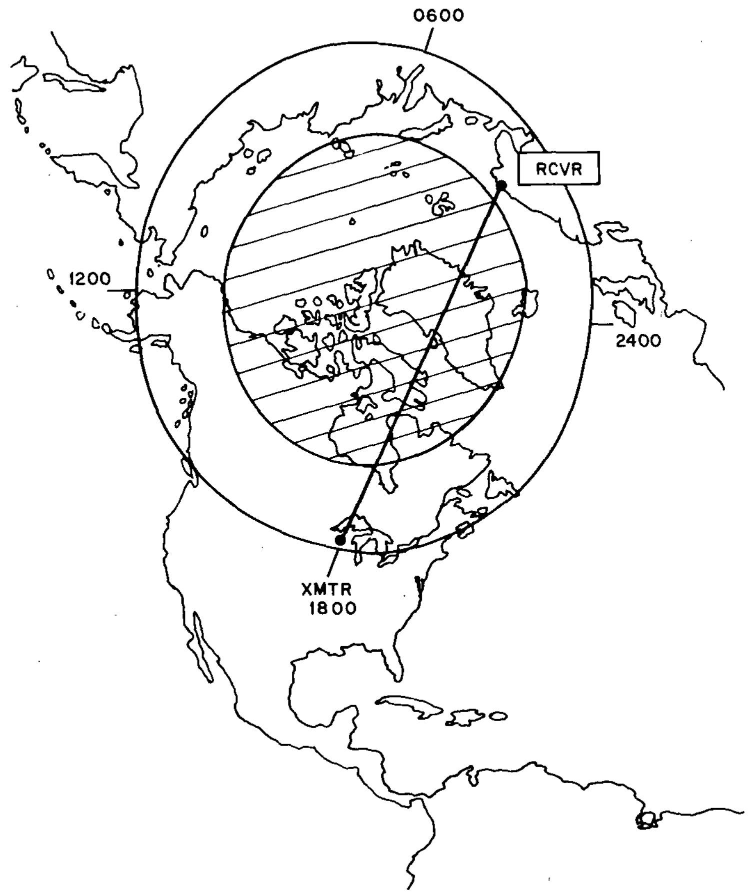

Fig. 3 — Southern limit of 1-10-MeV proton access to the northern hemisphere (inner ring). The outer ring designates the 60° geomagnetic parallel of latitude

path except for regions of several hundred kilometers extent near midpath, and at the receiver position. As a consequence of the limited portion of the path affected, auroral influence on ELF propagation probably will not consist of distributed effects such as a change in attenuation rate. Instead, they will involve variations in mode excitation due to changes in the conductivity of the waveguide upper boundary at the terminals of the path. It is for this reason that the receiver site at midnight is suggested as the likely worst condition, because only at that time will auroral particle precipitation be possible over either terminal. (For paths to the Mediterranean or the northern Pacific area, however, for which at certain times of day an ELF propagation path can coincide for much of its length with the auroral oval, distributed-path effects would be expected.)

Figure 6 is a graphical summary of the characteristics of precipitated auroral electrons. In Fig. 6 (a) it is seen that electrons in the 1-to-100-keV energy range have stopping heights between 80 and 120 km (15); in Fig. 6 (b) a representative integral energy spectrum (16) indicates the relative importance of electrons in this energy interval. Figure

6 (c) illustrates the height variation of ion-production rate for such an electron flux* (17); Fig. 6 (d) shows a possible resulting electron density profile. (At these altitudes electron conductivity dominates ion conductivity.) It is evident that the principal effects of auroral particle precipitation will be felt at altitudes above 80 to 100 km. Because ELF wave fields are confined to much lower altitudes in daytime (14,18), auroral disturbances will be principally a nighttime phenomenon in ELF propagation. Furthermore, since even at nighttime they will involve conductivity variations at altitudes above those at which most ELF absorption takes place, they will affect only the effective "shape" of the waveguide.

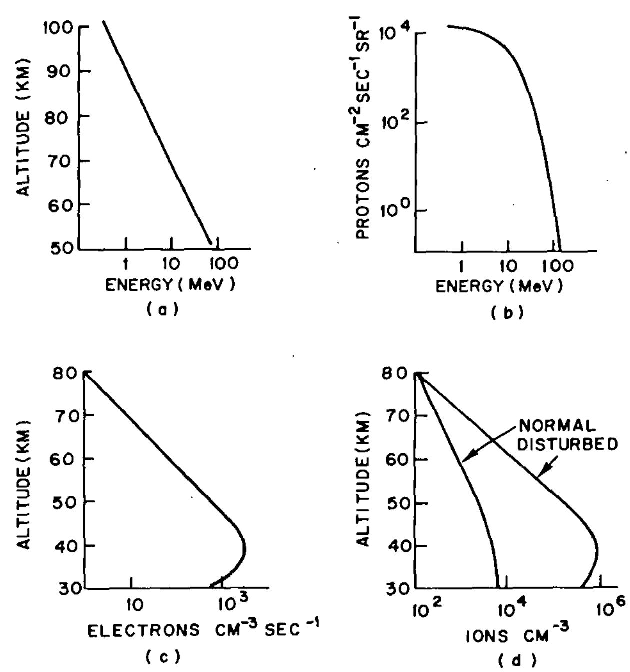

Fig. 4 — (a) Ionospheric stopping altitude for 1-100-MeV protons; (b) Integral energy spectrum for PCE protons; (c) Ionization production rate for PCE protons; and (d) Representative ion-density profile for normal and PCE nighttime conditions

One possible effect of auroral particle precipitation is related to the thickness, intensity, and geographical extent of auroral sporadic E (E_s), which is frequently present at night during auroral occurrences. Auroral E_s forms at altitudes between 90 and 120 km. It can take on the appearance of temperate latitude E_s, which is characterized by intense,

*This graph is not intended to indicate accurate absolute values and should be considered only as representative of the relative variation with height.

pancake-shaped layers a few kilometers thick and hundreds of kilometers in extent. In the case of auroral E_s, horizontal extent of hundreds of kilometers is probably a lower limit. Berkey et al. (19) indicate that strong auroral absorption events (indicative of large fluxes of precipitating electrons) may extend more than 10° in latitude and may occupy almost the entire auroral oval. Figure 7 indicates the degree to which E_s layers can constitute diffracting or reflecting bodies for ELF waves in the earth-ionosphere waveguide. This figure is a plot of apparent wavelength versus height for ELF waves of 75 Hz for a typical nighttime ionosphere. Apparent wavelength is defined here as the free-space wavelength divided by the real part of the refractive index. This form of display makes it possible for objects within the ionosphere to be evaluated regarding their significance as scatterers of ELF energy. Objects larger than an apparent wavelength constitute potentially important scattering bodies. The curve labelled "Galejs A" was used for attenuation rate calculations by Galejs (20), and this curve and the dashed line labelled "No E_s" define an area representing undisturbed nighttime conditions. Inserted at 100 km altitude are two cross-hatched areas which indicate the horizontal and vertical scale sizes of E_s layers. The typical horizontal extent of E_s layers is ample for them to constitute potential scattering bodies.

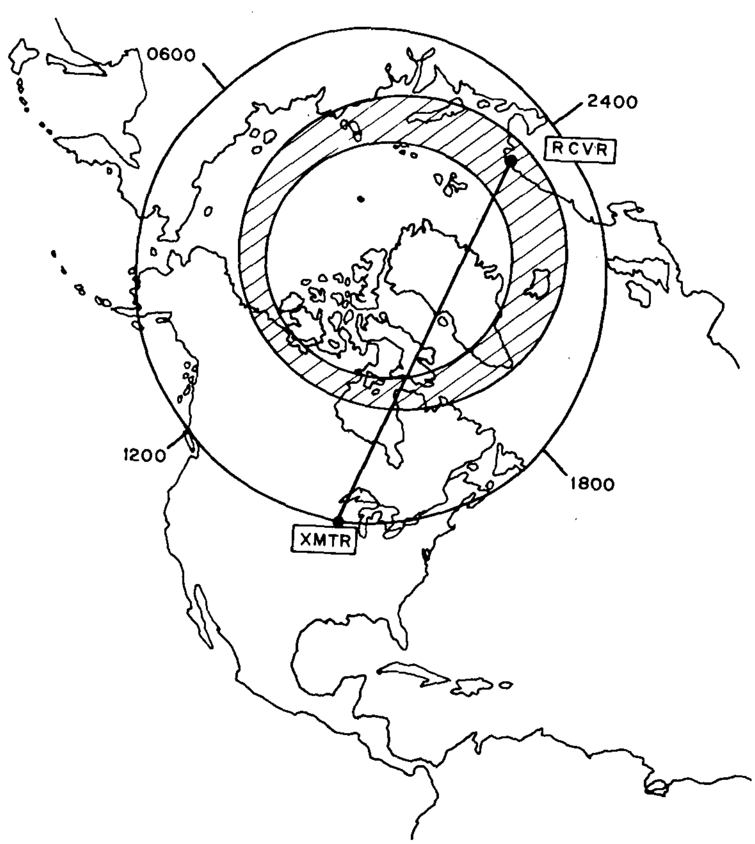

Fig. 5 — Precipitation oval for auroral electrons at receiver site at midnight (cross-hatched area)

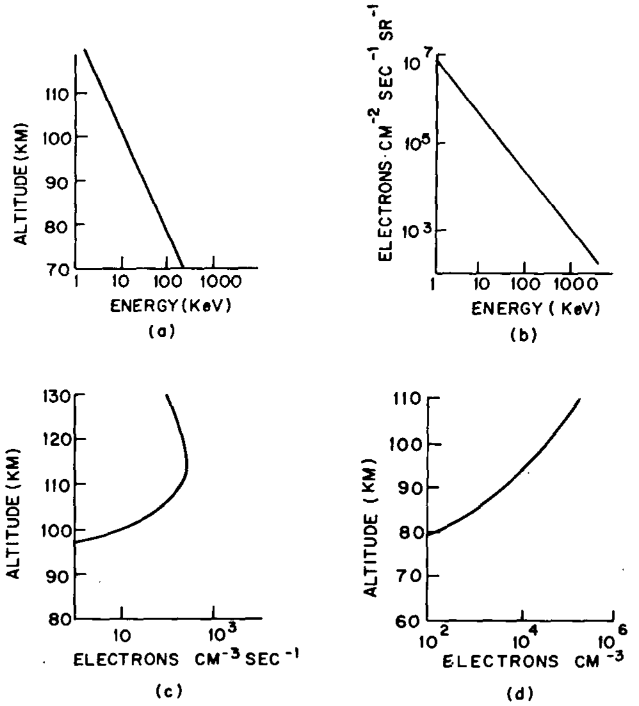

Fig. 6 — (a) Ionospheric stopping altitude for 1-300-keV electrons; (b) Integral energy spectrum for auroral electrons; (c) Ionization production rate for auroral electrons; and (d) Representative auroral D-region electron-density profile

The protuberances labelled "E_{s1}" and "E_{s3}" represent moderate to extreme E_s conditions, and it can be seen that the vertical scale of E_s exceeds the apparent wavelength of 75-Hz waves over a range of conditions between these two extremes. (Skin-depth would be a preferable criterion for evaluating the opacity of E_s layers to ELF waves, of course, but apparent wavelength as defined above is actually a more restrictive criterion.) It can be concluded that moderate to severe E_s of several kilometers thickness does constitute a sufficiently extensive and sufficiently opaque body to be of concern for reflecting ELF waves.

Auroral particle precipitation will result in the formation of time-varying discontinuities in waveguide height, or in the insertion of time-varying conducting bodies into the earth-ionosphere waveguide. The consequences of this type of disturbance in the vicinity of a path terminal will be changes in mode excitation efficiency. Because auroral precipitation is irregular in time, these changes in excitation may occur rapidly enough to interfere with coherent integration and hence may cause signal degradation.

In a slightly lower latitude region, extending from about 64° geomagnetic latitude through the auroral zone, the phenomenon of *relativistic*-electron precipitation (energies up to 1 MeV and higher) occurs occasionally and can affect the lower D-region. This phenomenon is an infrequent one and normally occurs following the expansion phase of a magnetospheric substorm. Its effects should last a few hours at most, but because of the high energies involved and consequent low-altitude region affected, it should give rise to significant ELF absorption during such a period. Relativistic electron-precipitation events can be expected to affect both dark and sunlit paths.

The third type of solar particle effect on the ionosphere occurs at subauroral to medium latitudes, where electrons are precipitated from the outer Van Allen belt. Figure 8 is a map showing the Wisconsin-Norway path and (cross-hatched) a portion of the precipitation zone for these electrons. For this path, the main effect of subauroral to mid-latitude particle precipitation will be felt over the transmitter site, but in the case of paths to points in the northern United States distributed influences on the entire path may be felt. The energy spectrum of precipitated subauroral particles may be somewhat softer than that shown in Fig. 6 (21), and hence the affected regions of the ionosphere may be slightly higher than those influenced by auroral particles.

The matter of principal concern here is that subauroral and mid-latitude electron-precipitation events occur more frequently than PCE or auroral-precipitation events and occur for up to 10 consecutive days in the period following solar eruptions (21,22,23,24). Furthermore, they are not invariably well-correlated with geomagnetic activity, especially in the lower part of the latitude interval involved (21); consequently, diagnosis can be difficult. The particle fluxes associated with these precipitation events are possibly one-tenth the values reached by strong auroral precipitation events, and so the resulting electron density peaks in the 100-km altitude region are somewhat less pronounced. However, if electron densities of one-tenth the representative value of 10^6 cm^{-3} shown in Fig. 6 (d) are achieved, they can be expected to have significant effects of the type described above in the discussion of auroral-precipitation influences.

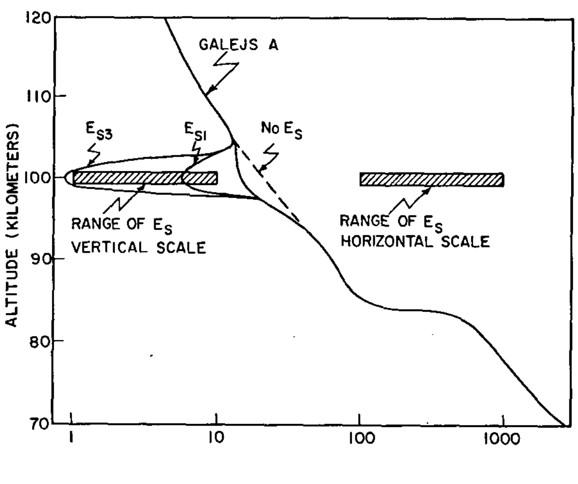

Fig. 7 — Apparent wavelength of 75-Hz ELF wave versus altitude. Under moderate to extreme E_s conditions, when the density of E_s compresses the apparent wavelength to less than the vertical extent of the layer (E_{s1} to E_{s3}), such a layer can constitute a significant reflecting body

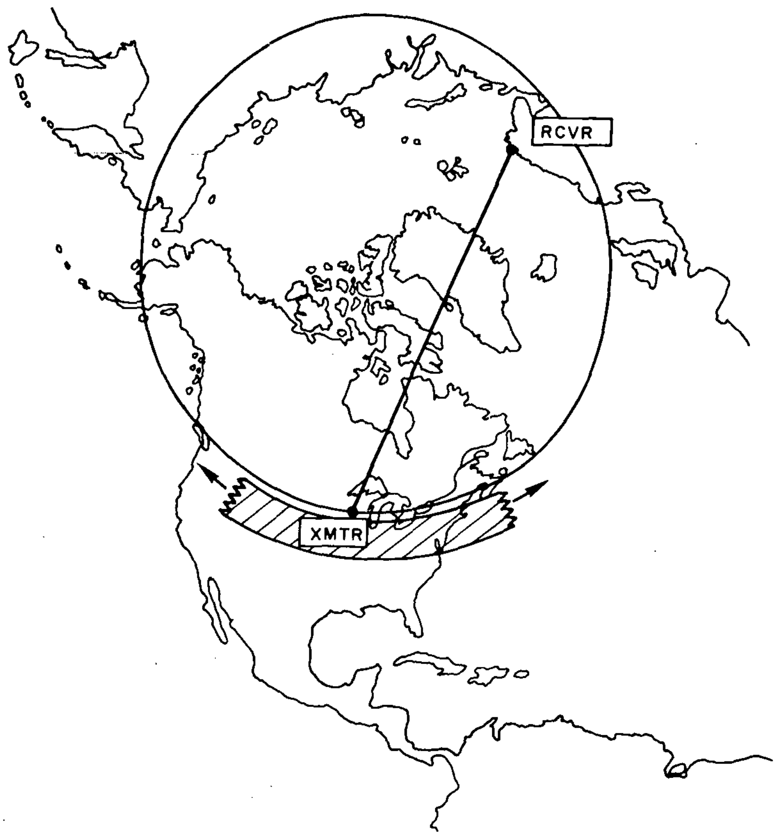

Fig. 8 — Precipitation region for electrons ejected from the outer radiation belt following magnetic storms

DIAGNOSTIC TOOLS

For average undisturbed ionospheric conditions involving propagation paths that are entirely sunlit or entirely dark, the propagation measurements reported by White and Willim (5) and Bannister (6) indicate substantial qualitative agreement between most theory and observations; the data confirm the expectation that attenuation rates of 0.8 to 1.0 dB/1000 km at night and 1.1 to 1.7 dB/1000 km during the day may be expected in the ELF band between 45 and 75 Hz. These measurements were not intended to deal with the effects of geomagnetic anisotropy and time-varying ionospheric phenomena, including passage of the twilight zone over the propagation path, that were described in the two preceding sections of this report and by Davis (1,8). During the course of these measurements, however, it became evident (a) that propagation-related ionospheric phenomena caused variations in received signal level that could not satisfactorily be ascribed to the influence of noise, (b) that those phenomena were most pronounced on dark paths, and (c) that they occurred most frequently on paths passing through northern latitudes. It was indicated above, furthermore, that fleeting changes in the ionosphere such as those associated with solar x-ray emissions and relatively rapid variations on the propagation path such as those associated with twilight effects could not be studied effectively. This circumstance results from the low radiated power of the existing ELF transmitter in Wisconsin and the consequent need for more than an hour of coherent integration at most receiving sites of interest.

Current investigations of ionospheric influence on ELF propagation are concentrated upon the northern latitude phenomena described above. A receiving site has been established at Tromsø, Norway, at the northern terminal of the path shown in Figs. 3, 5 and 8, and a second receiver site is planned near midpath at Frobisher Bay, Baffin Island. A third site is located well outside of the auroral region near Washington, D. C. Figure 9 shows the location of the receiving sites as well as the locations of ionospheric monitoring instruments that are in routine operation. These instruments are useful for diagnosing ionospheric disturbances associated with particle precipitation and are of four types, which are discussed in the following paragraphs.

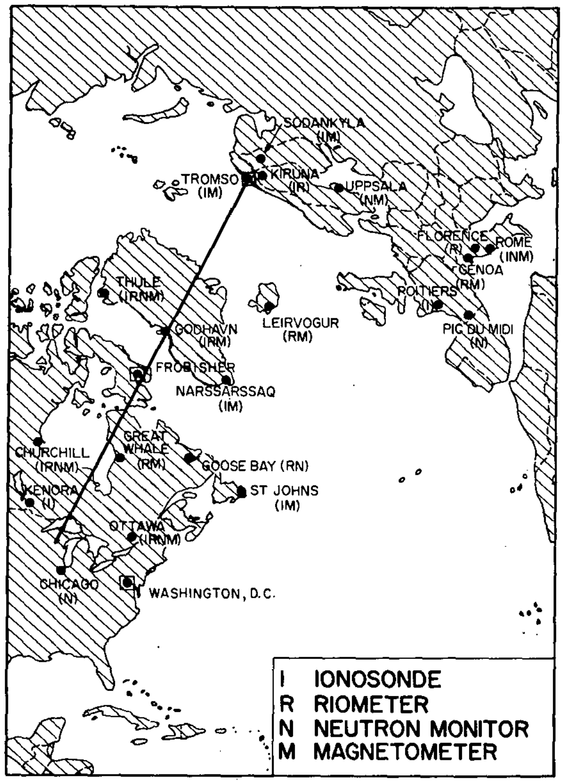

Fig. 9 — ELF receiving sites and ionospheric monitoring stations used in current propagation research. The line connects the transmitter in Wisconsin and the receiver in Norway

Ionosondes record the condition of the E region and should reveal the occurrence both of auroral E_s and of E_s at lower latitudes due to precipitation of trapped particles from the outer radiation belt. Thus the upper boundary of the ionospheric waveguide at points along the path and the existence of conducting irregularities at E-layer height within the waveguide under disturbed nighttime conditions should be discernible.

Riometers measure the absorption of cosmic radio noise due to D-region and lower E-region charged particles and should be of value for two important types of information. During PCE, of course, riometers in the polar cap reveal the arrival at the earth of the moderate-energy protons which are responsible for ionization enhancement in the D-region. This event is likely to be the most devastating of northern latitude phenomena upon ELF communications. In addition, however, riometers located in the auroral zone are capable of detecting the effects of precipitating auroral electrons. It is most important that such events be detected and mapped to as great a degree as possible. Auroral electron precipitation is quite irregular in time and spatial distribution, and its effects on ELF receiving sites can be expected to be equally irregular and localized.

Riometer data are important also because electron precipitation events are not always associated with a visible solar flare or with the emission of solar protons (24). Finally, on occasions when a solar eruption leads to emissions of both energetic electrons and protons, energetic electrons normally precede the protons deposited in the polar cap by several hours and hence provide warning of an imminent PCE (24).

Neutron monitors measure the intensity of galactic cosmic rays received at the surface of the earth. When low-energy solar plasma is emitted following a solar eruption, it proceeds outward from the sun; then upon approaching the earth, it compresses the interplanetary magnetic field and causes deflections of the incoming cosmic rays away from the earth. The resulting decrease in secondary neutron production is termed a Forbush decrease (9). The occurrence of a Forbush decrease thus heralds the approach of low-energy solar plasma, which propels ahead of it the moderate-energy protons responsible for the PCE.

Magnetometers serve several useful functions. At the beginning of a magnetospheric storm, the arrival at the earth of the shock-wave and, behind it, the low-energy plasma emitted by the sun often give rise to an abrupt increase in magnetic field known as a "sudden commencement". This event is of importance because it signals the arrival of the first large wave of protons capable of affecting the polar-cap D-region. These moderate-energy (1-to-10 MeV) protons are believed to be swept toward the earth by the interplanetary shock wave (9). The sudden commencement and Forbush decrease are both related to passage of this shock wave and normally occur simultaneously. Magnetospheric storms which give rise to these phenomena have the greatest likelihood of producing PCE's, and thus their observation on the earth represents a useful warning of potentially extensive ELF propagation disturbance.

Many magnetospheric storms do not produce sudden commencements, however, and in these cases it is not likely that large fluxes of moderate-energy protons are emitted by the sun. In such circumstances, the first evidence of the arrival of energetic charged particles at the earth is a gradual, large decrease in the horizontal component of the magnetic field. This event, which also occurs in sudden commencement storms several hours after the sudden commencement, signals the arrival of a large flux of low-energy protons and their formation into a diamagnetic ring current around the earth. While these protons are not energetic enough to reach the D-region at any latitude, the electrons accompanying them are injected into the outer Van Allen belt and are precipitated into the auroral zone over the period of several days following the solar eruption, causing substantial disturbance of the local D and lower E regions. These auroral substorms are responsible for the highly irregular pattern of auroral absorption which occurs principally in the morning sector of the auroral oval and involves rapidly moving, sporadic precipitation zones of a few hundreds of kilometers in size throughout this sector. Magnetometers are sensitive to the local geomagnetic variations which accompany auroral precipitation events and can be used to aid in the diagnosis of the resulting ionospheric disturbances.

MEASUREMENT RESULTS

Between 1970 and 1973 several months of multisite ELF propagation measurements were made by means of the ELF transmitter in Wisconsin for the purpose of determining average attenuation rates in the 40-to-50-Hz and 70-to-80-Hz bands. The results of most of these investigations were described by White and Willim (5) and Bannister (6). Very few of these measurements coincided with periods of ionospheric disturbance, and only a limited number of them involved northern latitude paths. Davis (8) and Bannister et al. (25) reported the few examples of probable ionospheric disturbance effects on ELF propagation that were acquired during this measurement program.

Observations have continued, on a limited basis, to gather further information on northern latitude ionospheric effects over the Wisconsin-Norway path mentioned above. A receiving site also is being maintained in intermittent operation in the northeastern United States to gather further data on subauroral effects.

The purpose of this discussion is to summarize previous observations of ELF propagation disturbance and to attempt to associate these observations with the ionospheric phenomena described in the two preceding sections. It should be understood that the low radiated power of the Wisconsin transmitter imposes severe limitations on the significance of measured signal information. Wave fields received in the bandwidth of about 5 Hz at most receiver locations are as much as 20 dB below atmospheric noise. Yet the expected signal variability due to ionosphere-related fluctuations in level is only a few decibels at most. Consequently, a large bandwidth reduction is necessary to achieve statistical significance of signal variations, and a method of synchronous detection is therefore needed to permit thousands of seconds of coherent integration to be achieved. In practice, integration time constants of more than 1 hour are employed. This procedure normally increases signal-to-noise ratio to 15 to 20 dB.

Furthermore, in order to insure statistical significance of signal variations, a careful measurement of ELF noise within the receiver bandwidth must be made continuously. On the assumption that this noise is gaussian over the narrow postdetection bandwidth, a measure of statistical significance can be determined in terms of signal-to-noise ratio.

For synchronous detection it may be assumed that the effect of noise on a desired signal is the introduction of randomness in phase. If this randomness is uniform (there is an equal probability of observing any random phase contribution), as would be the case for a gaussian noise field, the statistical problem reduces to one treated by Marcum

(26). The result of Marcum's treatment is a series of tabulations which permit a confidence interval to be established. For signals of a given apparent signal-to-noise ratio, the true value of a measurement will have a specified degree of assurance of falling within the confidence interval. In concurrence with White and Willim (5), ELF signal variations are accepted here as significant if they fall outside of the 80% confidence interval (strictly speaking, of course, one of every five such variations may be expected to be spurious). For the signal-to-noise ratio goal of 20 dB used in these measurements, the 80% confidence interval is slightly more than 2 dB in extent.

Propagation measurements at northern latitude receiving sites have coincided with indications of significant solar disturbance on only a few occasions. In October, 1971, a magnetic storm began on the morning (UT) of October 28. There was no sudden commencement, but on the following day a decrease in the horizontal magnetic field component of 920 γ was observed at College, Alaska. The geomagnetic index A_p reached a value of 27 on October 29, and during this 2-day interval a slight Forbush decrease was observed at several stations followed by gradual recovery by the end of the month. In this period, however, no significant increase in moderate-energy protons was observed by solar proton monitoring satellites.

ELF data from five receiving sites are shown in Fig. 10 for 10 nights, including the period of this disturbance. The heavy lines for each receiving location represent variations in the mean nightly data, and the 80% confidence interval for these mean data appears as a bounded vertical line, or "error bar" to the right of each graph. The irregular line segments distributed along each heavy line except the top one represent the variation of individual samples observed during each night. (Samples were taken so close together at Connecticut that they cannot be shown individually on the scale of this plot.) Transmitting frequency for each date is shown just above the horizontal axis. The frequencies are close enough together so that, for dark path conditions to the east of the transmitter, there should be no effect of standing waves due to interference between direct and around-the-world field components. Signal level at each of the top four sites is readily seen to have decreased abruptly by 2 to 5 dB between October 28 and 29, with Greenland showing the greatest drop. The Norway data do not follow the same pattern of behavior, but are highly irregular from night to night during this period.

This example has three strong implications:

- A solar eruption which does not yield large fluxes of energetic protons, can, nevertheless, affect a large portion of the ionosphere at auroral and medium latitudes.

- Its effects are well correlated in time with the occurrence of the magnetic storm and are qualitatively similar on paths which do not pass through the polar cap.

- Receiving stations across the polar cap from the transmitter are affected to as great a degree as those on the same side, but they follow much different temporal behavior.

These circumstances indicate that precipitating electrons at latitudes well below the auroral zone have a significant effect on ELF propagation. The appearance of the data in Fig. 10 suggests that stations at auroral latitudes and below are subject to an ionospheric

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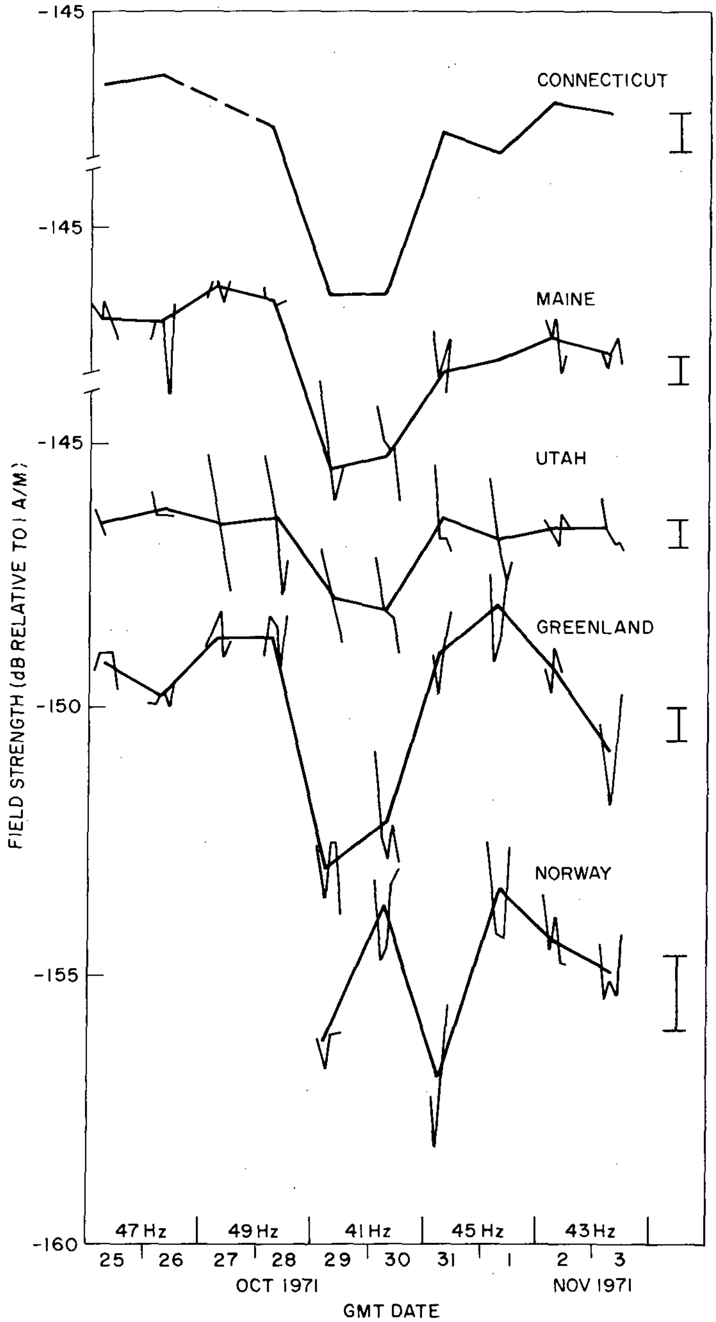

Fig. 10 — ELF nighttime field strength variations at five sites during the magnetic storm of October 28-30, 1971. The error bars at the right indicate the 80% confidence interval

effect that is not entirely uncorrelated; that is, the auroral precipitation and mid-latitude precipitation events seem to occur with roughly the same intensity over the same few days. The dissimilarity between the data from North America and Norway, however, indicates that these phenomena are not correlated over the entire auroral oval.

During the same period, daytime data for these stations displayed a similar but smaller two-day drop in field strength. The absence of evidence of a large flux of energetic protons approaching the earth during this time would indicate that precipitating electrons may have been responsible for the observed nighttime ELF signal variations; nevertheless, the daytime results are explainable only by concluding that the ionosphere must have been affected lower in the D region than can be reached by electrons of less than about 300 keV. A flux of undetected high-energy protons or of very-high-energy electrons is required. It is tempting to suggest that relativistic electrons may be responsible for this behavior, but the Connecticut and Utah paths do not reach geomagnetic latitudes higher than 55° to 58°, and relativistic electron precipitation events are not expected to have significant effects much below 65°.

Figure 11 contains a second example of disturbed behavior. Figure 11 has the same format as Fig. 10, except for a dotted line that has been added to the Norway data to indicate daytime behavior during the 10-day period shown. The North American sites all show similar behavior during this period, with a small but significant rise in signal level on October 17 and 18. The Greenland data are distinguished by dissimilarity to those from the three North American sites, but the variability is only moderate. The Norway data, however, are quite variable and show swings of nearly 4 dB from night to night on two occasions. The daytime data from Norway are also highly variable and, in contrast to the previous example, are not similar in pattern to the nighttime data — they are, indeed, much more similar to the data from the North American sites in this respect. The daytime and nighttime Norway data are similar, however, in that they both have the appearance of a transient waveform, as though the ionosphere had behaved like a low-pass filter excited by an impulse.

The evidence of specific geophysical stimulus for this behavior is less pronounced. A series of sudden-commencement magnetic storms had occurred in the first week of the month, with a large Forbush decrease from October 6 to 12 and an enhancement of 5- to 21-MeV solar protons between October 4 and 6. Although most of the effects of this eruption were completed by the beginning of ELF signal measurements on October 13, it is reasonable to suspect that a reservoir of energetic charged particles existed in the radiation belts and continued to precipitate into the northern latitude ionosphere during this period. The extreme variability of the Norway data indicates that the principle effect of this precipitated flux occurred in the polar cap and hence was probably a proton effect. The dissimilarity between the Greenland data and those from the North American sites indicates that precipitation of particles into the auroral zone also had an effect on propagation, however small. This example suggests that solar eruptions which result in energetic proton emission can affect polar ELF paths for a period of several days and can have an influence on both sunlit and darkened paths.

Other examples of disturbed ELF propagation that are reasonably well correlated with geophysical activity, as well as a number of less satisfying cases, are treated by Davis (8).

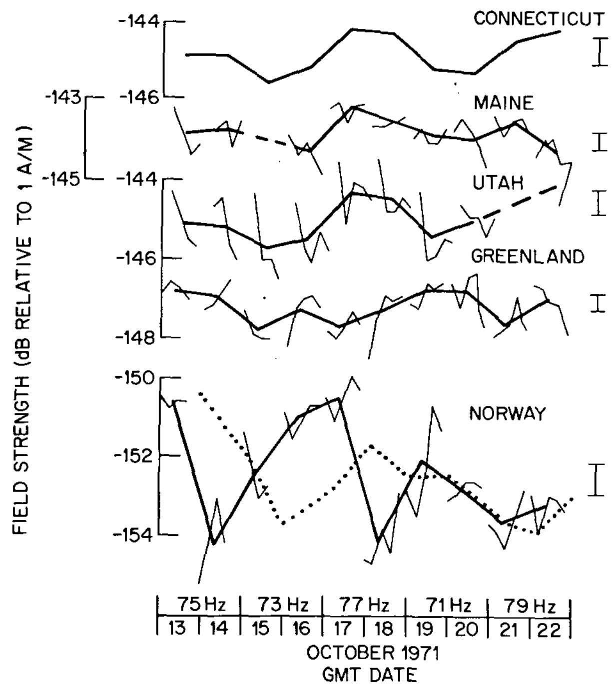

Fig. 11 — ELF nighttime field-strength variations during the period following the magnetic storms of early October 1971. Daytime data for the Norway site are shown dotted

There is another class of disturbance that has been observed frequently on short, mid-latitude paths, but which may have only a minor effect on auroral and polar paths (the evidence is not yet conclusive on the latter point). This class of disturbance consists of a decrease in signal strength of 2 to 6 dB, which is observed to take place over a period of about 4 hours, followed by a gradual return to normal. Figure 12 is a montage of five three-night data sequences in which this class of disturbance is exhibited. Data are averaged over a 1-hour period, and the 80% confidence interval for these 1-hour averages is shown to the right of each graph. The dashed lines indicate the variation of mean signal level from night to night (except for the January 25-26, 1974, graph, in which the normal level is shown for the third night). These data were acquired in Connecticut (provided by Bannister through private communication in 1974) and display the following general features:

- Normal signal levels on the first night are followed on the second night by a decrease in mean signal level of 2 to 3 dB.

- The signal decreases over a period of about 4 hours during the second night to a level as much as 6 dB below normal.

- Recovery generally begins immediately.

- The recovery is complete by the beginning of the third night.

It is evident in the top three graphs of Fig. 12 that a very similar, consistent signal-level decline occurred during the middle night of the sequence and that recovery began right away. The data from October 30 to November 1, 1973, do not show the steep signal decrease; accordingly, it can be speculated that the perturbing influence commenced between the first and second nights. The data from October 31 to November 2, 1972, show a significant signal-level *increase* the first night, followed by an abrupt decrease, with gradual recovery the second night.

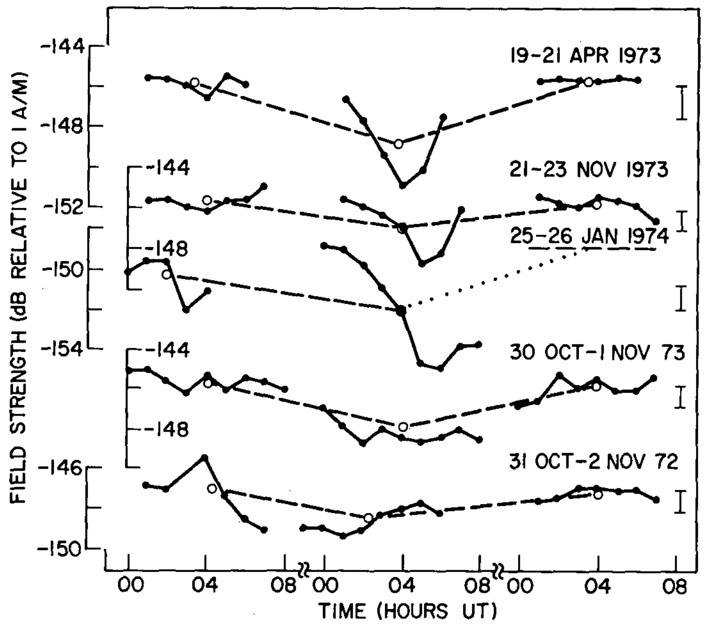

Fig. 12 — ELF nighttime field strengths recorded in Connecticut during five three-night periods in which large decreases in signal level were observed

Evidence of geophysical disturbance accompanied each of these events. Several large, sudden commencement magnetic storms occurred between April 14 and 16, 1973, with effects lasting until April 20. (ELF data began April 17, so the early effects of these storms were not observed.) A moderate magnetic storm commenced November 21, 1973, reaching a peak of magnetic activity a few hours before the data sequence shown for November 22. A large magnetic storm began January 25, 1974, (available data are still fragmentary for this case). A large magnetic storm began on October 28, 1973, and lasted until the end of that month. A solar proton event and large magnetic storm occurred between October 29 and November 2, 1972. In all cases, these short-path observations indicate that the large decrease in ELF signal strength occurred in the few days following the peak of magnetic activity. It is reasonable to suggest that the effects observed are a result of charged particles dumped from the outer radiation belt following their insertion into the trapping zone during the early stages of the magnetic storms.

In only one case (the bottom graph of Fig. 12) were data acquired during the early stages of the charged-particle effects on the ionosphere; and this example shows interesting behavior. Several large solar x-ray flares occurred between October 24 and 31, 1972, with a particularly large one at 0400 UT on October 31. Solar proton monitors detected a large, enhanced flux of energetic protons between 0400 and 0800 UT October 31. A large Forbush decrease commenced coincident with the proton flux increase and persisted until November 6. A PCE was observed at Thule, Greenland, beginning late October 30 and persisting until early November 1. A sudden commencement magnetic storm began at 1654 UT on October 31, achieving a peak change in horizontal magnetic field of 2170 γ at Sitka, Alaska, and a maximum A_p of 98 on November 1. The proton flux returned to near normal by early November 1, and the geomagnetic storm ended on November 3.

The signal level in the bottom graph of Fig. 12 began to increase rapidly at about 0200 UT October 31, peaked at 0400 UT, and declined rapidly for the rest of that night. This sequence of events slightly preceded the large proton-flux peak observed by satellites. The unusually low signal levels observed the following night coincided with the end of the PCE and the return of the solar-proton flux to its predisturbance level.

Because the initial signal-level increase preceded the proton-flux increase measured by satellite, it is tempting to associate this rise in level with the arrival in the atmosphere of the energetic electrons that often precede the protons by a few hours (24). The effect of these electrons would be to increase electron density in the E and upper D regions and thus increase the conductivity of the ionospheric waveguide boundary. Hence, less wave energy would leak out of the normally diffuse nighttime waveguide, and received fields would be increased. The later arrival of protons in the energy range above 10 MeV would cause increased absorption in the D region, but these protons would probably not have access to the latitudes of the Wisconsin-Connecticut path unless the geomagnetic field was greatly compressed during the main phase of the magnetic storm. Such an event began during the early morning of November 1, and it was during this period that the second night's low signal levels were received.

The final example suggests the degree to which these short-path effects may be local in nature and confined to the subauroral to mid-latitude range. Figure 13 contains the Connecticut data from Fig. 12, together with data acquired simultaneously in Maryland (about 4° lower in geomagnetic latitude) and in Norway. The Connecticut data show a pronounced 6-dB drop in signal level the second night between 0000 UT and 0400 UT, whereas the Maryland data show only a slight dip — of little significance in comparison with the 80% confidence interval but well correlated with the Connecticut signal behavior. The Maryland site is approximately 500 km from the one in Connecticut, but pathlengths to the two locations from the Wisconsin transmitter are not significantly different. The Norway data during these three nights were normal.

It is evident from the data in Fig. 13 that localized ionospheric effects can occur even at mid-latitudes (the geomagnetic latitude of Connecticut is 55°) and can lead to significant signal variations.

CONCLUSION

The most promising result of this analysis is an indication that solar influence upon ELF propagation is associated with the various indices of charged particle arrival in the

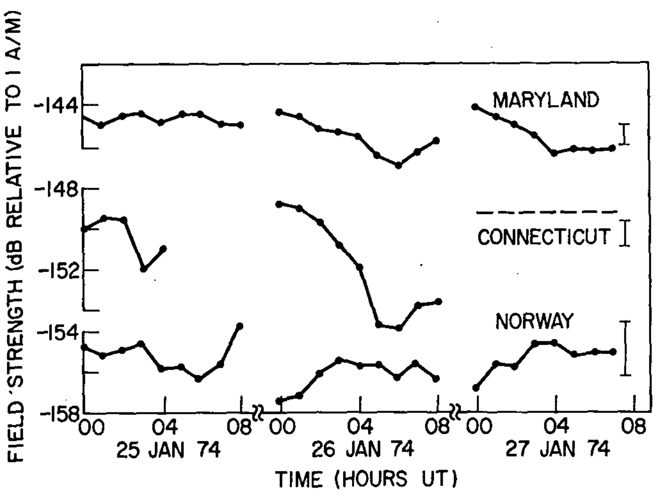

Fig. 13 — ELF nighttime field strengths from two North American sites and Norway showing localized ionospheric effect

vicinity of the earth. Decreases in galactic cosmic ray intensity and the onset of magnetic storms are most consistently associated with the observed ELF propagation anomalies.

It must be noted, however, that the degree of seriousness of these effects should not be overestimated. In no case does the evidence indicate that net degradation exceeds several decibels. All of these results are based on data that were integrated over tens of minutes to hours. Having established that even with this limitation there is evidence of significant solar/geophysical influence on ELF propagation, one should begin to ask whether shorter term influences also exist, and whether these influences might have an important effect on transmissions at higher data rates. It should be evident that propagation research efforts continue to be necessary and will benefit from a transmitter of increased radiating capacity.

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