

Summary of ELF Propagation Validation System Field Strength Measurements, 1976 to 1978

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(Invited Paper)

Abstract—From August 1976 through December 1978, extremely low frequency (ELF) field strength and effective noise measurements were taken continuously in Connecticut and sporadically aboard operational submarines. This article summarizes the field strength measurements taken at both land (Connecticut) and sea (North Atlantic, Western Pacific) locations during January, March, April, and October 1977 and January/February 1978. The main conclusion is that the average field strengths measured aboard the submarines (which were located at distances of 4–12 Mm from the Wisconsin Test Facility) are in excellent agreement with previous ELF measurements taken over similar paths. Anomalous ELF field strength variations were also correlated with geomagnetic activity. Interference between the direct and “round-the-world” paths was probably observed during the Western Pacific area daytime propagation period in early October 1977. ELF propagation effects were also observed during the February 13, 1978, significant solar particle event.

I. INTRODUCTION

THE ELF¹ PROPAGATION validation system (PVS) is composed of the U.S. Navy's extremely low frequency (ELF) Wisconsin Test Facility (WTF) and ELF receivers (AN/BSR-1) installed on submarines and at certain land sites. The WTF is located in the Chequamegon National Forest in north-central Wisconsin, about 8 km south of the village of Clam Lake. It consists of two 22.5-km antennas: one antenna is located approximately in the north-south (NS) direction, and one is located approximately in the east-west (EW) direction. Each antenna is grounded at both ends. At 76 Hz, the electrical axis of the NS antenna is 14° east of north, while the electrical axis of the EW antenna is 114° east of north. The WTF antenna array can be steered electrically toward any particular location. Its radiated power is approximately 1 W.

The AN/BSR-1 receiver is composed of an AN/UYK-20 minicomputer, a signal timing and interface unit (STIU), a rubidium frequency time standard, two magnetic-tape recorders, and a preamplifier. The message output is on a teletype (TTY), which is used to control the receiver. The submarine receiving antenna is a buoyant cable 1.6 cm in diameter with electrodes spaced 300 m apart on a 580-m transmission line.

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¹ ELF (formerly called SANGUINE/SEAFARER) is an arbitrary designation applied to ongoing extremely low frequency research by the U.S. Navy. The term designates work directed toward the implementation of an ELF shore-to-ship radio communication system.

The system uses minimum shift keying (MSK) modulation with a center frequency of 76 Hz. The signaling scheme uses block orthogonal coding to make maximum use of the limited transmitter power available. This scheme provides the most efficient use of the transmitter for short messages.

During January 1977, three submarines involved in testing were located in the North Atlantic/Norwegian Sea area at a range of approximately 5 Mm from WTF. During March 1977, one submarine was located in the North Atlantic area at a range of approximately 4 Mm from WTF while another was located near Hawaii. During April 1977, the submarine involved in testing was located under the ice in the Greenland Sea at a range of approximately 4.5 Mm from WTF.

During early October 1977, one submarine was located in the North Atlantic area at a range of approximately 4.5 Mm from WTF, while another was located in the Western Pacific area at a range of approximately 11.5 Mm from WTF. During late October 1977, the Western Pacific area submarine was located at a range of approximately 8.5 Mm from WTF.

During January 1978, one submarine involved in testing was located in the North Atlantic/Norwegian Sea area at a range of approximately 4.5–5 Mm from WTF, while another test submarine was located in the Western Pacific area at a range of approximately 10 Mm from WTF. During February 1978, the North Atlantic area submarine was approximately 4–4.5 Mm from WTF. Signal-strength (both amplitude and relative phase), effective-noise², and signal-to-noise ratio (SNR) data were recorded automatically whenever the ELF receiving antenna was streamed, though no special operational posture was adopted to provide ELF reception.

In the submarine data, the depth and orientation are automatically accounted for by the receiver. The submarine data analyzed in this article have been taken at essentially constant depth and orientation for considerable periods of time. We also have a substantial amount of unreduced (as far as signal amplitude and phase are concerned) submarine data where the speed, depth, and orientation of the submarine were varying considerably. These particular data are not too useful for obtaining accurate signal amplitude and phase information.

² The effective-noise spectrum level is defined as the spectrum level of ELF noise at the signal frequency minus the improvement in the level of the signal-to-noise ratio (SNR) using nonlinear processing [1]. The unit of effective-noise spectrum level is the decibel with respect to the reference quantity of one ampere per meter in a one-hertz band. The unit symbol is dB re 1 Am⁻¹ Hz^{-1/2}.

However, they are very useful for obtaining information on messages received during submarine maneuvers.

In this article, we will summarize the principal results of the 1976-1978 land (Connecticut) and sea ELF field-strength measurements. For further details, see Bannister [2]-[7].

II. DATA INTERPRETATION

For distances sufficiently removed from the region of the antipode, the farfield horizontal magnetic field strength component (H_ϕ) produced by the WTF array (normalized with respect to the EW antenna at a current of 300 A) may be expressed in dB re 1A/m as [8], [9], [10]:

$$20 \log H_\phi \cong K + 20 \log E - \alpha \rho - 10 \log (a \sin \rho/a) + 20 \log \frac{F(\phi)}{B} \quad (1)$$

where $K = 139.1$ dB at 76 Hz, and $E = (h_{KM} \sqrt{\sigma_{EW}} \sqrt{c/v})^{-1}$ is defined as the earth-ionosphere waveguide excitation factor (note that E is inversely proportional to the product of the effective ionospheric reflecting height h (in kilometers) times $\sqrt{\sigma_{EW}}$). Also where

- σ_{EW} effective earth conductivity beneath the WTF EW antenna $= 3.2 \times 10^{-4}$ mho/m at 76 Hz [10],
- c/v ratio of free space to earth-ionosphere waveguide phase velocity,
- α earth-ionosphere waveguide attenuation rate (dB/Mm),
- ρ great-circle distance between WTF and receiver (Mm),
- a radius of the earth ($\cong 6.37$ Mm), and
- $F(\phi)/B$ WTF array pattern factor, which equals unity in the direction of the EW antenna axis [11].

From (1), we see that for a two-site measurement program the only unknowns to be determined are α and E , assuming that the excitation factor is the same at both receiving sites. We have also shown [9] that α is directly proportional to E . That is, at 76 Hz, $\alpha \cong 1.4E$ dB/Mm. Since α is directly proportional to E , field-strength measurements could be taken at just one site to obtain average values of α and E for a particular measurement period.

The average daytime and nighttime attenuation rates inferred from the 1976-1978 Connecticut measurements alone were 1.25 and 0.9 dB/Mm, respectively, while the excitation factors were -1.0 dB during the day and -3.8 dB at night. The average relative phase velocity difference between daytime and nighttime propagation conditions [$\Delta(c/v)$] was 0.15. These values of α and $\Delta(c/v)$ are in good agreement with previous measurements taken over similar paths [8], [9], [12].

The normalized 1977-1978 North Atlantic area average field strengths measured during six different time periods are presented in Table I, while a comparison of the 1977-1978 PVS North Atlantic area predicted and measured field strengths is presented in Fig. 1. The data are all normalized to a WTF antenna phasing factor of 0 dB (i.e., $F(\phi)/B = 1.0$).

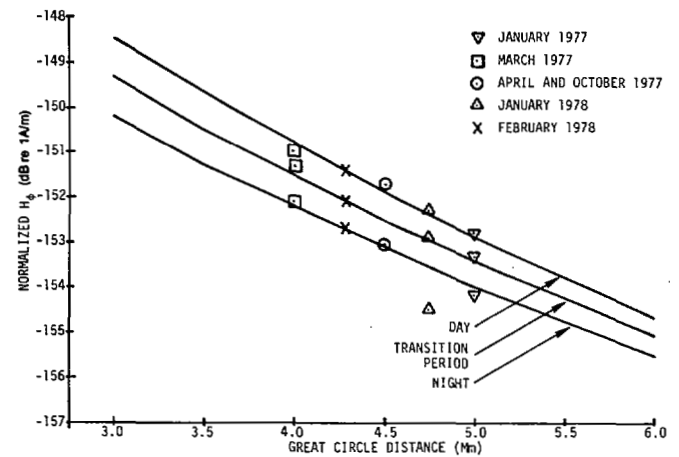


Fig. 1. Comparison of 1977-1978 North Atlantic area predicted and measured field strengths.

TABLE I
1977-1978 NORTH ATLANTIC AREA AVERAGE FIELD STRENGTHS IN
dB re 1A/m (NORMALIZED TO $F(\phi)/B = 1$)

Time	January 1977 H_ϕ	March 1977 H_ϕ	April 1977 H_ϕ	October 1977 H_ϕ	January 1978 H_ϕ	February 1978 H_ϕ	1977-78 Average H_ϕ
Day	-152.8	-151.0	-151.7	-151.7	-152.3	-151.3	-151.8
SSTP	-152.7	-150.9	-151.2	-151.8	-152.5	-151.9	-151.8
Night	-154.2	-152.1	-153.0	-153.1	-154.5	-152.7	-153.2
SRTTP	-153.5	-151.7	-151.8	-151.8	-153.3	-152.0	-152.3
Average TP	-153.3	-151.3	-151.5	-151.8	-152.9	-152.0	-152.1
$\Delta\phi$ (deg)	56	60	-	60.5	64	56	59
Average Distance (Mm)	5.0	4.0	4.5	4.5	4.75	4.25	4.5
$\Delta(c/v)$	0.12	0.16	-	0.15	0.15	0.14	0.145

The average range from WTF was 4-5 Mm. The predicted values are based on the above-mentioned values of attenuation rate (1.25 and 0.9 dB/Mm) and excitation factor (-1.0 and -3.8 dB). Note that, with the exception of the January 1978 nighttime measurements, the predicted values are in excellent agreement with the measured values at all five locations.

Referring again to Table I, we see that the North Atlantic area average measured difference in relative phase ($\Delta\phi$) between the nighttime and daytime propagation periods was 59° during 1977-1978. For an average range of 4.5 Mm, this translates to a $\Delta(c/v)$ of 0.145, which is almost identical to the 0.15 value inferred from the Connecticut measurements alone.

From our previous measurements [8], [9], [12], we have observed that during daytime propagation conditions, the attenuation rate in the EW direction is approximately 0.3 dB/Mm greater than that in the west-east (WE) direction at 75 Hz. This is in agreement with the theoretical work of Galejs [13] who showed that below 100 Hz the attenuation-rate differences between EW and WE directions will be slight.

The daytime and nighttime attenuation rates inferred from the March/April 1971 Utah/Hawaii measurements were 1.5 and 0.9 dB/Mm, respectively, while the excitation factors were $+0.3$ during the day and -3.3 dB at night [8], [9], [12].

Based on an analysis of all the Pacific area PVS measure-

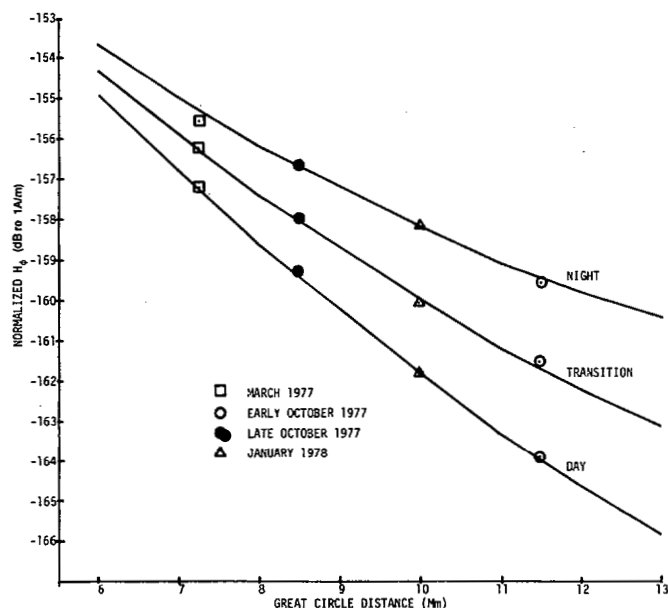


Fig. 2. Comparison of 1977-1978 Western Pacific area predicted and measured field strengths.

ments, it appears that the attenuation rates and excitation factors inferred from the March/April 1971 Utah/Hawaii measurements also apply to the general Pacific area, with the exception of the nighttime excitation factor. This appears to be -2.1 dB (1.2 dB higher). It is interesting to note that the only other long-path Pacific area ELF measurements (i.e., Alaska/Saipan, May 1972 [8], [9]) resulted in a 75-Hz nighttime excitation factor of -4.5 dB, which was 1.2 dB lower than measured during March/April 1971.

A comparison of the 1977-1978 PVS Western Pacific area predicted and measured field strengths is presented in Fig. 2. The data are all normalized to a WTF antenna phasing factor of 0 dB (i.e., $F(\phi)/B = 1.0$). During March 1977, late October 1977, January 1978, and early October 1977, respectively, the range from WTF was approximately 7.25, 8.5, 10.0, and 11.5 Mm. The predicted values are based on the above-mentioned values of attenuation rate (1.5 and 0.9 dB/Mm) and excitation factor (+0.3 and -2.1 dB). Note that the predicted field strengths are in excellent agreement with the measured field strengths at all four locations during daytime, transition period (TP), and nighttime propagation conditions.

III. "ROUND-THE-WORLD" INTERFERENCE

From September 30 to October 5, 1977, the Western Pacific area submarine was located at a range of approximately 12 Mm from WTF. The average measured field strengths were -163.2 dB re 1A/m during the day and -159.9 dB re 1A/m at night [6]. Based on the March/April 1971 values of attenuation rate (1.5 and 0.9 dB/Mm) and excitation factors (+0.3 and -3.3 dB), the predicted field strengths at a range of 12 Mm are -163.3 dB re 1A/m during the day and -159.7 dB re 1A/m at night, which are also in excellent agreement with the measured field strengths.

There is also another valid interpretation that can be applied to the September 30-October 5 12-Mm range nighttime field strengths. An assumed attenuation rate of 0.8 dB/

Mm and an excitation factor of -4.5 dB would yield a predicted nighttime field strength of -159.7 dB re 1A/m. These are the same values of attenuation rate and excitation factor inferred from the May 1972 Alaska/Saipan measurements [8], [9].

Presented in Fig. 3 is a plot of the September 30-October 8 individual field strength values for the daytime propagation period of 20 00 to 24 00 GMT. Here, we see that, during each of these days, the field strength decreased 6 dB from 20 00 to 21 30, then increased 5 dB from 21 30 to 24 00. The time of minimum field strength (≈ 21 30) is about 1 h after sunrise in the Western Pacific.

The probable cause of this dip is interference between the direct and "round-the-world" paths. Since both the transmitting and receiving areas are in sunlight, both paths will be characterized by the higher (daytime) excitation factor. However, the direct path will be characterized by the higher (daytime) attenuation rate (1.5 dB/Mm), while the "round-the-world" path will be mainly characterized by the lower (nighttime) attenuation rate (≈ 0.8 dB/Mm).

Assuming that one-half of the world is in darkness and the other half is in daylight, the difference in attenuation between the direct and "round-the-world" paths is $20(0.8) + 8(1.5) - 12(1.5) = 28 - 18 = 10$ dB.

The maximum peak-to-trough variations (MPTV) in the interference pattern will be equal to the sum of the two waves divided by their difference. That is,

$$\text{MPTV} = \left| \frac{e^{-\alpha_D \rho_D} + e^{-\alpha_R \rho_R}}{e^{-\alpha_D \rho_D} - e^{-\alpha_R \rho_R}} \right| \quad (2)$$

where α is the attenuation rate and ρ is the great-circle distance. The subscripts D and R refer to the direct and "round-the-world" waves.

For the case under consideration, $\alpha_D \rho_D = 18$ dB (2.072 N) and $\alpha_R \rho_R = 28$ dB (3.224 N). Inserting these values in (1) results in $\text{MPTV} = 1.92$ (5.7 dB), which is almost identical to the measured results of 5-6 dB.

IV. CORRELATION WITH GEOMAGNETIC ACTIVITY

Because some previous ELF field-strength variations appeared to be correlated with geomagnetic activity [14]-[16], it would be of interest to compare the 1976-1978 measurements with geomagnetic activity. Presented in Figs. 4 and 5 are daily comparisons of the normalized 1976 Connecticut minimum field strengths (measured during a 1-h period) with the geomagnetic A_K index for Fredericksburg, VA. The minimum values are nighttime data except for the August 23 and 24 data, when abnormally low daytime field strengths were measured [2]. The normalized factor (-145.7 dB re 1A/m) is the average value of the nighttime field strength measured in Connecticut from 1970 to 1974 [17]. Different WTF phasings have also been accounted for (i.e., the reference ψ is 21°).

It is readily apparent from Figs. 4 and 5 that during August-December 1976, increases in geomagnetic activity were usually accompanied by decreases in the minimum nighttime field strength measured at the Connecticut site. The principal

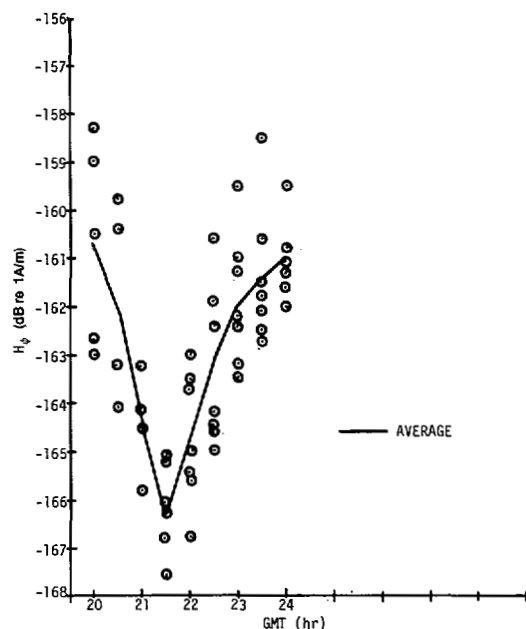


Fig. 3. Western Pacific area strengths versus GMT (20 00-24 00 GMT), September 30, to October 8, 1977.

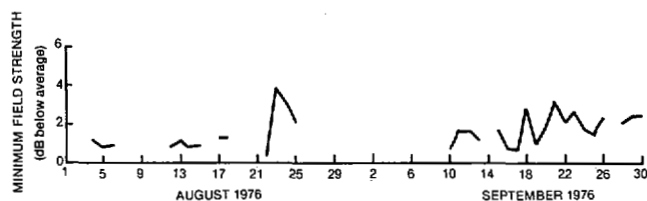


Fig. 4. Daily comparisons of minimum Connecticut nighttime field strength with geomagnetic behavior—August/September 1976.

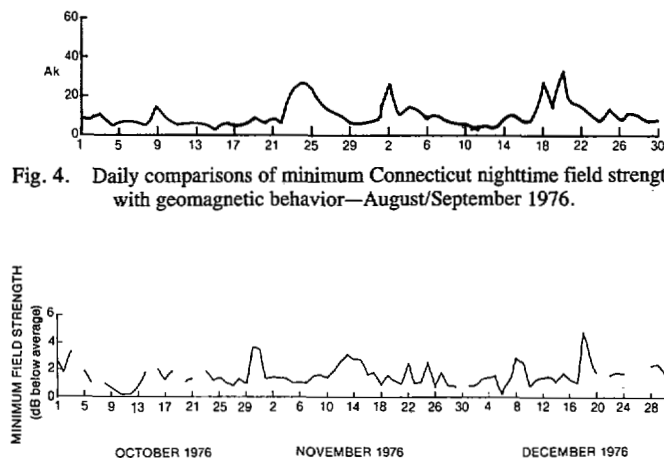
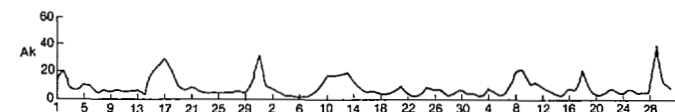
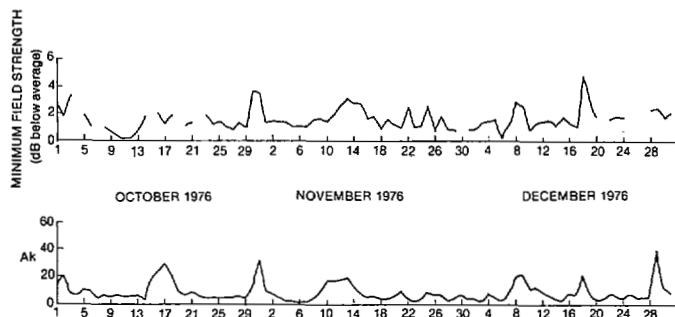


Fig. 5. Daily comparisons of minimum Connecticut nighttime field strength with geomagnetic behavior—October, November, and December 1976.



exceptions to this trend occurred during October 16-18 and on December 29 (Fig. 5), however, the average daytime field strength measured on these dates was approximately 1 dB lower than normal. Furthermore, the $\Delta\phi$ value measured during December 29 was only 12° , which was 8° less than the monthly average.

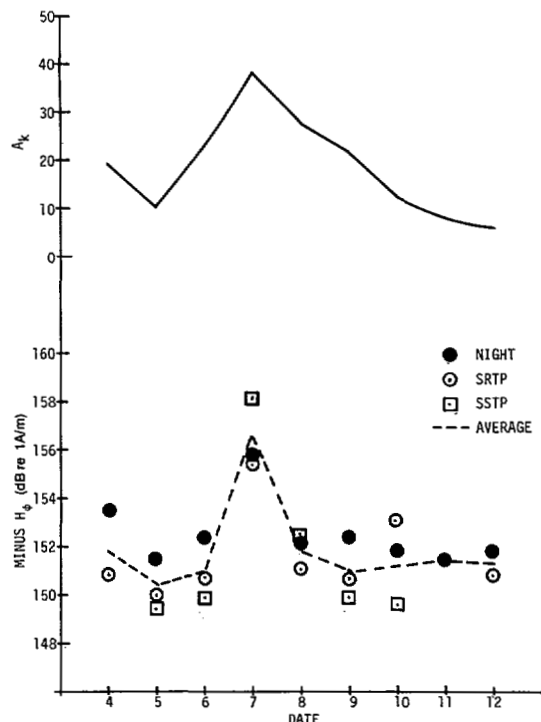


Fig. 6. Daily comparisons of Greenland Sea area average SSTD, nighttime, and SRTP field strengths with geomagnetic behavior, April 4-12, 1977.

It is also observed from Figs. 4 and 5 that the time period between the lowest measured minimum nighttime field strengths is approximately 25-28 days. This reception period is nearly equal to the solar rotation period of 27 days.

Presented in Fig. 6 are the daily comparisons of the average sunset transition period (SSTD), nighttime, and sunrise transition period (SRTP) field strengths (measured in the Greenland Sea area from April 4 to 12, 1977) with the geomagnetic A_K index for Fredericksburg, VA. (Note that $-H_\phi$ is plotted versus day of month).

It is readily apparent from Fig. 6 that, during this particular period, increases in geomagnetic activity were accompanied by decreases in the SSTD, nighttime, and SRTP field strengths. In particular, during April 7, when magnetic activity was the greatest, the measured field strengths were the lowest.

On numerous occasions during the last decade, the ELF nighttime field strength measured at various sites in the northeastern United States has displayed rapid decreases of from 4 to 8 dB in several hours. Additional examples of localized ELF nighttime field strength variations also occurred during the 1976-1978 measurement period. These variations were not restricted to measurement locations in the northeastern United States. In particular, simultaneous Connecticut and North Atlantic area measurements were characterized by nighttime propagation anomalies occurring 2-4 h apart. A candidate for the cause of these anomalies is a moving nocturnal sporadic E layer. For further details, see Bannister [4], [6], [18].

V. ELF PROPAGATION MEASUREMENTS DURING A PCA EVENT

Turtle *et al.* [19] have recently provided a summary of disturbance effects of energetic-particle events on very low

frequency/low frequency (VLF/LF) propagation parameters, as observed by the U.S. Air Force High Resolution VLF/LF Ionosounder in northern Greenland during 1978. Disturbance effects on ionospheric reflectivity parameters, including reflection heights and coefficients, were presented along with data from a riometer, a magnetometer, and satellite particle detector.

One of the strongest 1978 solar-particle events occurred in February during the transition period from night conditions in December to day-night conditions in March (at local noon, the sun just barely reached the horizon at Thule). A polar cap absorption (PCA) (6-dB riometer absorption) began at 09 50 GMT on February 13 and the time of maximum 13–25 million electronvolts (MEV) proton flux was 06 00 on February 14. This event caused a 28-km drop in the VLF noontime reflection height at Thule, followed by a gradual return to normal over the next 7 days. Even at night, during the first day of the event, the reflection height remained 25 km lower than normal due to the continued high particle-flux rate. For the next several days, however, there was a strong diurnal variation which was not present before or after the event. This variation was probably caused by a combination of particle-produced ionization with varying photo-detachment and attachment processes. As the sun approached the horizon, photodetachment produced increased electron densities, lowering the reflection heights. After local noon, as the solar zenith angle increased, the effective reflection heights increased due to attachment [19].

Effects from the February 13, 1978, solar-particle event were also observed on the North Atlantic area submarine, which was located approximately 3 Mm southeast of Thule [7].

For the period February 1–12 immediately preceding the event, the North Atlantic area average values for field strength (both amplitude and relative phase), SNR, and effective-noise are plotted in Fig. 7 versus GMT. From this figure, we see that the highest field strengths were measured around WTF sunrise (13 00 GMT), while the lowest field strengths were measured during the 05 00–07 00 GMT portion of the nighttime period. The average daily effective-noise variation was approximately 4 dB, with the minimum values measured during the early morning hours (02 00–04 00 GMT) and the maximum values measured during the late afternoon and early evening hours (19 00–21 00 GMT). The average night-to-day relative-phase variation was 60° , which for a range of 4.2 Mm, translates to a $\Delta(c/v)$ of 0.16.

Presented in Fig. 8 are the North Atlantic area data for February 13, 1978, the day of the event. Comparing this figure with Fig. 7, we see that the February 13 nighttime field strengths were slightly higher (≈ 1 dB) than the February 1–12 average, while the SSTP and daytime field strengths were approximately the same. However, at the PCA starting time (≈ 10 00 GMT), the relative phase abruptly dropped to the daytime value, 3 h before WTF sunrise!

The February 14–16 North Atlantic area submarine data are plotted in Fig. 9 versus GMT. The 21 00 to 02 00 SSTP and nighttime field strengths were 1–1.5 dB higher than the February 1–12 average (Fig. 7), while the 02 00–15 00 field

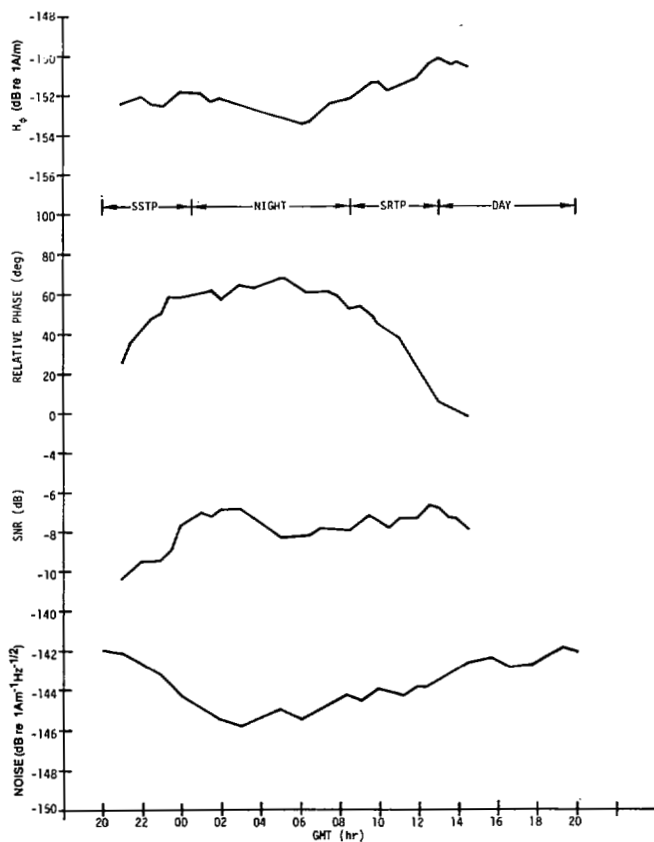


Fig. 7. North Atlantic area average data versus GMT ($\psi = 291^\circ$), February 1–12, 1978.

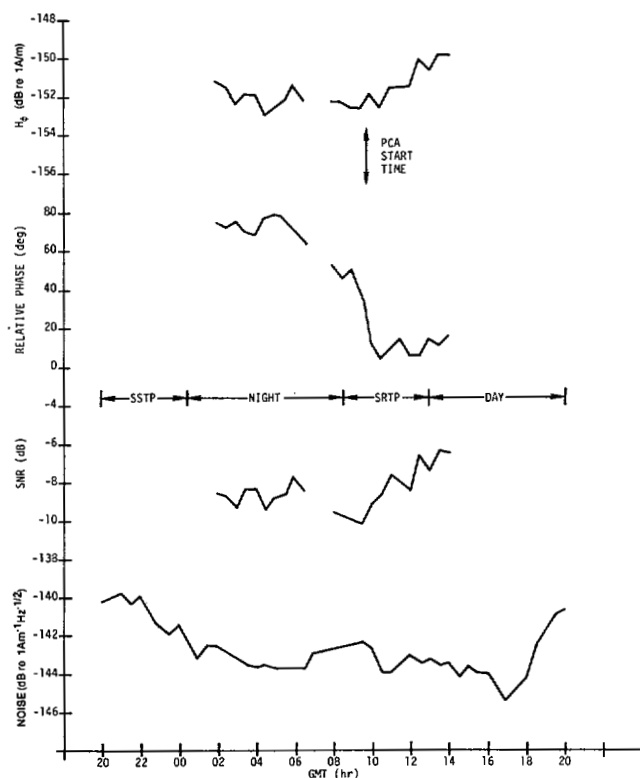


Fig. 8. North Atlantic area average data versus GMT ($\psi = 291^\circ$), February 13, 1978.

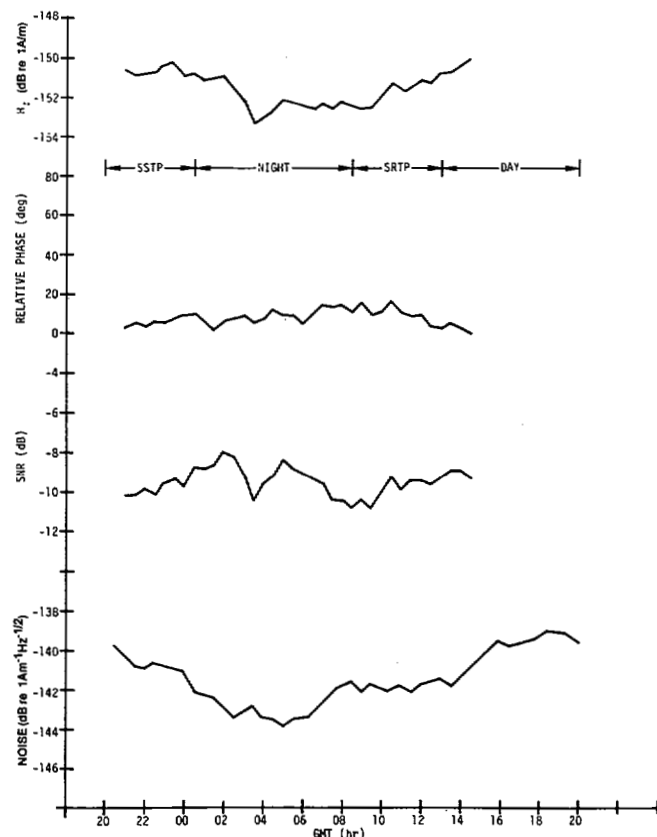


Fig. 9 North Atlantic area average data versus GMT ($\psi = 291^\circ$), February 14-16, 1978.

strength was about the same as that measured on February 13, (Fig. 8). However, the average night-to-day relative-phase variation was *only* 7° as compared to the 60° average value measured from February 1-12.

This substantial $\Delta\phi$ variation is further illustrated in Fig. 10, which is a plot of the February 1-20, 1978, North Atlantic area daily average relative-phase variation versus day of the month. From this plot, we see that from February 5 to 11, $\Delta\phi \cong 60^\circ$, the February 1-12 average value. During February 12, $\Delta\phi$ increased to 88° , then returned to normal on February 13. However, during February 14, $\Delta\phi$ decreased to -6° , then gradually increased to its normal value by February 18. The average night-to-day relative-phase variation was approximately 0° during February 14 and 15, which corresponds to a $\Delta(c/v)$ of zero. This also implies a decrease in the nighttime reflection height of 25-30 km during these two nights.

At the Connecticut measurement site, the February 13-15 average $\Delta\phi$ variation was approximately 18° , as compared to the monthly average of 19° . Thus the effect of the February 13, 1978, PCA on the Connecticut nighttime reflection height was minor.

VII. CONCLUSIONS

This article summarizes the 1976-1978 ELF field-strength measurements taken continuously in Connecticut and sporadically aboard operational submarines. The principal conclusion is that the average field strengths measured aboard the submarines (which were located at distances of 4-12 Mm from

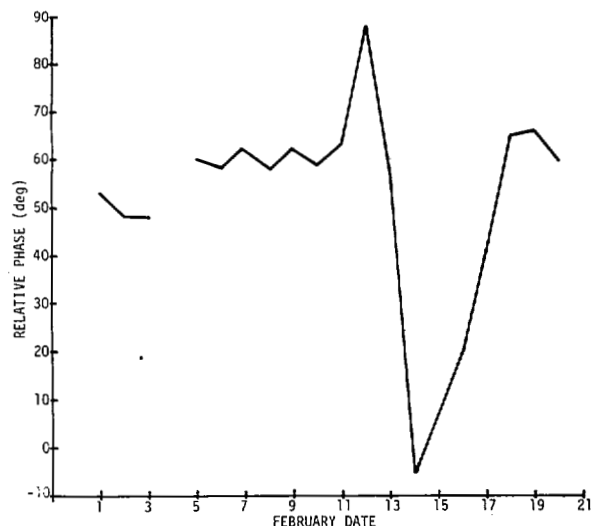


Fig. 10. North Atlantic area daily average relative phase versus date, February 1-20, 1978.

WTF), are in excellent agreement with previous ELF measurements taken over similar paths.

Anomalous Connecticut and Greenland Sea area field-strength variations were also correlated with geomagnetic activity. That is, increases in geomagnetic activity were usually accompanied by decreases in the received field strengths.

Interference between the direct and "round-the-world" paths was probably observed during the Western Pacific area daytime propagation period in early October 1977. The measured peak-to-trough variation in the interference pattern was 5-6 dB, compared with the predicted value of 5.7 dB.

ELF propagation effects were also observed during the February 13, 1978, significant solar particle event. When the PCA started (3 h before WTF sunrise), the North Atlantic area relative phase immediately dropped to the daytime level and remained there for two days (which implies a decrease in the nighttime reflection height of 25-30 km).

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Peter R. Bannister (M'69), for a photograph and biography please see p. 163 of this issue.