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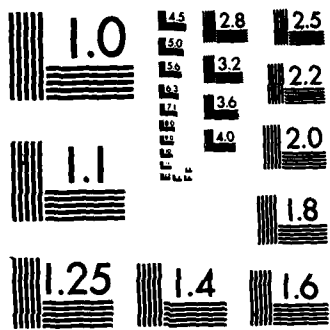
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NUSC Technical Report 6775  
3 February 1983

# ELF PVS Field Strength Measurements, January and February 1978

Peter R. Bannister  
Submarine Electromagnetic Systems Department

AD A 126208



**Naval Underwater Systems Center**  
Newport, Rhode Island / New London, Connecticut

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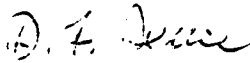
## **Preface**

This report was prepared under NUSC Project No. A59007, "ELF Propagation RDT &E" (U), Principal Investigator, P. R. Bannister (Code 3411). Navy Program Element No. 11401N and Project No. X0792-SB, Naval Electronic Systems Command Communications Systems Project Office, D. Dyson (Code PME 110), Program Manager ELF Communications, Dr. B. Kruger (Code PME 110-XI).

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The Technical Reviewer for this report was Raymond F. Ingram.

**Reviewed and Approved: 3 February 1983**



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## GLOSSARY OF ABBREVIATIONS

ELF	<u>Extremely low frequency</u>
EW	East-west
GMT	Greenwich Mean Time
LF	Low frequency
MEV	Million electron volts
MSK	Minimum shift keying
NS	North-south
NUSC	Naval Underwater Systems Center
PCA	Polar cap absorption
PVS	<u>Propagation validation system</u>
SNR	Signal-to-noise ratio
S RTP	Sunrise transition period
SSTP	Sunset transition period
STIU	Signal timing and interface unit
TTY	Teletype
VLF	Very low frequency
WE	West-east
WTF	Wisconsin Test Facility

## ELF PVS FIELD STRENGTH MEASUREMENTS, JANUARY AND FEBRUARY 1978

## INTRODUCTION

The ELF\* 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 deg east of north, while the electrical axis of the EW antenna is 114 deg east of north.<sup>1</sup> 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.

The system uses minimum shift keying (MSK) modulation with a center frequency of 76 Hz. The signalling 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 1978, one submarine involved in testing was located in the North-Atlantic area at a range of approximately 4.5 to 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 to 4.5 Mm from WTF. Signal-strength (both amplitude and relative phase), effective-noise, 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 report 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

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\*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.

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

In this report, we will discuss the results of these January and February 1978 submarine field-strength measurements and will compare them with simultaneous measurements taken in Connecticut.

#### JANUARY 1978 WESTERN-PACIFIC-AREA RESULTS

During this time period, data were taken for about a week aboard the Western-Pacific-area submarine, which was located at a range of approximately 10 Mm from WTF. Unfortunately, the measured effective noise\* was contaminated by submarine-generated noise (internal or external to the submarine), resulting in poor SNR's and few field-strength samples per day.

The average of the limited amount of Western-Pacific-area field-strength (both amplitude and relative phase), SNR, and (contaminated) effective-noise measurements is presented in figure 1.† From this curve, we see that the diurnal field-strength variation was -7 dB, while the (contaminated) effective-noise variation was only 3 dB.

From our previous measurements,<sup>3,4</sup> 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,<sup>5</sup> 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 dB during the day and -3.3 dB at night.<sup>3,4,6</sup>

Based on an analysis of all the Pacific-area PVS measurements, 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<sup>3,4</sup>) resulted in a 75-Hz nighttime excitation factor of -4.5 dB, which was 1.2 dB lower than that measured during March/April 1971.

The average January 1978 Western-Pacific-area (-10 Mm from WTF) daytime, transition period, and nighttime measured field strengths were -160.5, -158.8, and -156.9 dBA/m, respectively. Based on the abovementioned values of

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\*The effective-noise spectrum level (in dBA/m· $\sqrt{1}$  Hz) is defined as the spectrum level of ELF noise at the signal frequency divided by the improvement (in SNR) using nonlinear processing.<sup>2</sup>

†Figures have been placed together at the end of this report or in the applicable appendix.

attenuation rate (1.5 and 0.9 dB/Mm) and excitation factor (+0.3 and -2.1 dB), the predicted field strengths at a range of 10 Mm are -160.5, -158.7, and -156.9 dBA/m, respectively, which are almost identical to the measured field strengths.

Referring to figure 1, we see that the average Western-Pacific-area measured difference in relative phase ( $\Delta\phi$ ) between the nighttime and daytime periods was approximately 105 deg. For a range of 10 Mm, this translates to a  $\Delta(c/v)$  of 0.115, which is very close to the 0.12 value measured in the North-Atlantic area during January 1977.<sup>7</sup>

A comparison of the 1977-78 PVS Western-Pacific-area predicted and measured field strengths is presented in figure 2. The data are all normalized to a WTF antenna phasing factor of 0 dB (i.e.,  $F(\phi)/B = 1.0$ ). During March, early October, and late October 1977, respectively, the range from WTF was approximately 7.25, 8.5, and 11.5 Mm. The predicted values are based on abovementioned 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, and nighttime propagation conditions.

#### JANUARY 1978 NORTH-ATLANTIC-AREA RESULTS

During this time period, data were obtained on 12 days from the North-Atlantic-area submarine. Unfortunately, no data were obtained from the Connecticut site, because the microwave link connecting the Fisher's Island, NY, receiving antenna to the Naval Underwater Systems Center (NUSC) receiver at New London, CT, was not operating. The daily plots of the North-Atlantic-area signal strength (both amplitude and relative phase), effective noise, and SNR versus Greenwich Mean Time (GMT) are presented in appendix A. The WTF antenna phasing angle ( $\psi$ ) was 291 deg throughout January and the transmitting frequency was  $76 \pm 4$  Hz.

Presented in table 1\* are the January 1978 North-Atlantic-area submarine daily field-strength averages. The data are broken up into four time periods, which should be representative of

1. Nighttime propagation conditions (-0000 to 0800 GMT),
2. Sunrise transition period (SRTP) propagation conditions (-0800 to 1330 GMT),
3. Daytime propagation conditions (-1330 to 2000 GMT), and
4. Sunset transition period (SSTP) propagation conditions (-2000 to 2400 GMT).

Referring to table 1, we see that there is a considerable day-to-day variation in the received field strengths. That is, the average field strength

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\*All tables are placed together at the end of this report.

sometimes changes by 2 to 4 dB from one day to the next. This phenomenon is typical of ELF propagation on northern latitude paths.<sup>7-12</sup>

The January 1978 average field-strength (both amplitude and relative phase), SNR, and effective-noise values are plotted in figure 3 versus GMT. From this figure, we see that the highest field strengths were measured around the beginning of the daytime measurement period (1300 to 1400 GMT), while the lowest field strengths were measured during the 0400 to 0600 GMT portion of the nighttime period. The average daily effective-noise variation was approximately 5 dB, with the minimum values measured during the early morning hours (0700 to 0900 GMT) and the maximum values measured during the late afternoon and early evening hours (1900 to 2100 GMT).

A plot of the January 1978 North-Atlantic-area SNR distribution ( $N \approx 410$  30-min samples) is presented in figure 4. From this curve, we see that the predetection (in a 1-Hz bandwidth) SNR at optimum heading was greater than -10 dB 50 percent of the time and greater than -14 dB 98 percent of the time. The postdetection SNR (after a 30-min integration time) was greater than 22.5 dB 50 percent of the time and greater than 18.5 dB 98 percent of the time.

During January, March, April, and October 1977, field-strength measurements were taken in Connecticut and aboard submarines located in the North-Atlantic/Norwegian-Sea area. The daytime and nighttime attenuation rates inferred from these measurements 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.<sup>7-10</sup> These values are consistent with previous measurements taken over similar paths.<sup>3,4</sup>

Referring to table 1, we see that the average January 1978 North-Atlantic-area ( $\sim 4.75$  Mm from WTF) daytime, transition period, and nighttime measured field strengths were -152.3, -152.9, and -154.5 dBA/m, respectively. Based on the abovementioned values of attenuation rate and excitation factor, the predicted field strengths at a range of 4.75 Mm are -152.4, -153.0, and -153.6 dBA/m, respectively. Note that there is excellent agreement between the measured and predicted daytime and transition-period field strengths. On the other hand, the measured nighttime field strengths were approximately 1 dB lower than predicted, which was probably caused by a decrease in the nighttime excitation factor.

Referring again to table 1, we see that the average North-Atlantic-area measured difference in relative phase ( $\Delta\phi$ ) between the nighttime and daytime periods was -64 deg. For a range of 4.75 Mm, this translates to a  $\Delta(c/v)$  of 0.15, which is the average value measured in the North-Atlantic area during 1977-78.

#### FEBRUARY 1978 CONNECTICUT RESULTS

For the Connecticut measurements, the AN/BSR-1 receiver is located in Room 3111 of Building 80, at NUSC. The loop receiving antenna is located at Fisher's Island, about 10 km from New London. The receiver and receiving antenna are connected by means of a microwave link. The receiving antenna is located approximately 50 m from an NUSC building at Fisher's Island which houses the ELF preamplifier and associated circuitry.

During February 1978, the WTF antenna phasing angle ( $\psi$ ) was 291 deg and the transmitting frequency was  $76 \pm 4$  Hz.

Listed in table 2 are the February 1978 Connecticut daily field-strength averages (both amplitude and relative phase) for the 18 days on which measurements were made. The monthly average measured field strengths were -143.4, -144.2, and -145.8 dBA/m during daytime, transition period, and nighttime propagation conditions.

For a WTF antenna phasing angle of 291 deg, the average Connecticut field strength should equal  $\sim$ -143.3, -144.4, and -145.5 dBA/m during daytime, transition period, and nighttime propagation conditions (assuming the same attenuation rates and excitation factors as the WTF/North-Atlantic path). Thus, the monthly average measured field-strength levels are about as expected.

The February night-to-day average relative-phase variation was 19 deg, which corresponds to a monthly average  $\Delta(c/v)$  of 0.13. The largest relative-phase variation (26 deg) occurred on 18 February, while the smallest relative-phase variation (14 deg) occurred on 6 February.

Figures 5 through 10 are the February Connecticut daily field-strength plots. The effective noise was not plotted because it was contaminated by industrial noise throughout most of February.

Amplitude peak-to-trough variations of 5 dB or greater occurred during only 1 of the 18 measurement days, on 22 February (figure 9). The highest average nighttime field strength (-144.4 dBA/m, -1.4 dB above the monthly average) was measured on 6 February (figure 5), which was also when the smallest night-to-day relative-phase variation (14 deg) occurred. The lowest nighttime field strength (-148.8 dBA/m, -3 dB below the monthly average) was measured from 0530 to 0630 GMT on 22 February (figure 9).

The highest average daytime field strength ( $\sim$ -143.0 dBA/m, -0.4 dB above the monthly average) was measured during 3 to 12 February (figures 5 and 6), while the lowest average daytime field strength ( $\sim$ -144.0 dBA/m, -0.6 dB below the monthly average) was measured during 20 to 26 February (figures 8 through 10). These daytime field-strength differences will be discussed in more detail in the next section.

During the transition period, the highest average field strength ( $\sim$ -143.3 dBA/m, -0.9 dB above the monthly average) was measured on 27/28 February (figure 10), while the lowest average field strength (-145.0 dBA/m, -0.8 dB below the monthly average) was measured on 20, 25, and 26 February (figures 8 through 10).

#### FEBRUARY 1978 NORTH-ATLANTIC-AREA RESULTS

During this time period, data were obtained on 24 days from the North-Atlantic-area submarine. The daily plots of signal strength (both amplitude and relative phase), effective noise, and SNR are presented in appendix B. The WTF antenna phasing angle ( $\psi$ ) was 291 deg during February and the transmitting frequency was  $76 \pm 4$  Hz.

Presented in table 3 are the February 1978 North-Atlantic-area submarine daily field-strength averages. The data are broken up into four time periods which should be representative of

1. Nighttime propagation conditions (-0030 to 0830 GMT),
2. Sunrise transition period (SRTP) propagation conditions (-0830 to 1300 GMT),
3. Daytime propagation conditions (-1300 to 2000 GMT), and
4. Sunset transition period (SSTP) propagation conditions (-2000 to 0030 GMT).

During January, March, April, and October 1977, field-strength measurements were taken in Connecticut and aboard submarines located in the North-Atlantic/Norwegian-Sea area. The daytime and nighttime attenuation rates inferred from these measurements 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.<sup>7-10</sup> These values are consistent with previous measurements taken over similar paths.<sup>3,4</sup>

Referring to table 3, we see that the average February North-Atlantic-area (~4.25 Mm from WTF) daytime, transition period, and nighttime measured field strengths were -151.3, -152.0, and -152.7 dBA/m, respectively. Based on the abovementioned values of attenuation rate and excitation factor, the predicted field strengths at a range of 4.25 Mm are -151.3, -152.0, and -152.7 dBA/m, respectively, which are identical to the average monthly measured values.

Referring again to table 3, we see that the measured average difference in relative phase ( $\Delta\phi$ ) between the nighttime and daytime periods was 56 deg during February. For a range of 4.25 Mm, this translates to a  $\Delta(c/v)$  of 0.14, which is very close to the 0.13 value inferred from the Connecticut measurements alone.

A plot of the February 1978 North-Atlantic-area SNR distribution (N = 805 30-min samples) is presented in figure 11. From this curve, we see that the predetection (in a 1-Hz bandwidth) SNR at optimum heading was greater than -9 dB 50 percent of the time and greater than -14 dB 98 percent of the time. The postdetection SNR (after a 30-min integration time) was greater than 23.5 dB 50 percent of the time and greater than 18.5 dB 98 percent of the time.

The normalized 1977-78 North-Atlantic-area average field strengths measured during six different time periods are presented in table 4, while a comparison of the 1977-78 PVS North-Atlantic-area predicted and measured field strengths is presented in figure 12. The data are all normalized to a WTF antenna phasing factor of 0 dB (i.e.,  $F(\phi)/B = 1.0$ ). The average range from WTF was 4 to 5 Mm. The predicted values are based on the abovementioned 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.



Turtle et al.<sup>13</sup> 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 detectors.

Since 1978 was a very active year, ionospheric disturbance effects of 16 energetic-particle events were reported.<sup>13</sup> The characteristics of the effects of energetic particles on the VLF/LF propagation parameters are a function of event size and solar-illumination conditions. The reflection heights for both parallel and perpendicular components drop coincident with the influx of energetic particles. The level to which the height drops depends on the magnitude of the particle flux and the solar-illumination conditions during the event.<sup>13</sup>

One of the strongest solar-particle events occurred in February 1978 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 0950 GMT on 13 February and the time of maximum 13-25 million electron volts (MEV) proton flux was 0600 on 14 February. This event caused a 28 km drop in noon-time 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 photodetachment 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.<sup>13</sup>

A short-lived (1-day) low-energy event also occurred on 25 February. The ionospheric disturbance started at 1555 GMT and the time of maximum 13-25 MEV proton flux was 2000 GMT. This event caused a 20-km decrease in the 16-kHz reflection height.

Effects from the 13 February 1978 solar-particle event were also observed on the North-Atlantic-area submarine, which was located approximately 3 to 5 Mm southeast of Thule.

The 1 through 12 February North-Atlantic-area average field-strength (both amplitude and relative phase), SNR, and effective-noise values are plotted in figure 13 versus GMT. From this figure, we see that the highest field strengths were measured around WTF sunrise (~1300 GMT), while the lowest field strengths were measured during the 0500 to 0700 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 (0200 to 0400 GMT) and the maximum values measured during the late-afternoon and early-evening hours (1900 to 2100 GMT). The average night-to-day relative-phase variation was 60 deg, which, for a range of 4.2 Mm, translates to a  $\Delta(c/v)$  of 0.16.

Presented in figure 14 are the 13 February 1978 North-Atlantic-area data. Comparing this figure with figure 13, we see that the 13 February nighttime field strengths were slightly higher (~1 dB) than the 1 to 12 February average, while the SSTP and daytime field strengths were approximately the same. However, at the PCA starting time (~1000 GMT), the relative phase abruptly dropped to the daytime value, 3 hr before WTF sunrise!

The 14 to 16 February North-Atlantic-area submarine data are plotted in figure 15 versus GMT. The 2100 to 0200 SSTP and nighttime field strengths were 1 to 1.5 dB higher than the 1 to 12 February average (figure 13), while the 0200 to 1500 field strength was about the same as that measured on 13 February (figure 14). However, the average night-to-day relative-phase variation was only 7 deg as compared to the 60 deg average value measured from 1 to 12 February (figure 13)!

This substantial  $\Delta\phi$  variation is further illustrated in figure 16, which is a plot of the 1 to 20 February 1978 North-Atlantic-area daily average relative-phase variation versus day of the month. From this plot, we see that from 5 to 11 February,  $\Delta\phi \sim 60$  deg, the 1 to 12 February average value. During 12 February,  $\Delta\phi$  increased to 88 deg, then returned to normal on 13 February. However, during 14 February,  $\Delta\phi$  decreased to -6 deg, then gradually increased to its normal value by 18 February. The average night-to-day relative-phase variation was approximately 0 deg during 14 and 15 February, which corresponds to a  $\Delta(c/v)$  of zero. This also infers a decrease in the nighttime reflection height of 25 to 30 km during these two nights.

Referring to the 13 to 15 February Connecticut relative-phase data (table 2 and figures 6 and 7), we see that the 15 February  $\Delta\phi$  variation was only 15 deg, as compared to the monthly average of 19 deg. However, the 13 to 15 February average  $\Delta\phi$  variation was -18 deg, which is comparable to the monthly average. Thus, the effect of the 13 February 1978 PCA on the Connecticut nighttime reflection height was minor.

The 17 to 19 February North-Atlantic-area submarine average data are plotted versus GMT in figure 17, while the 20 to 25 February data are plotted in figure 18. From these curves, we see that the field strengths are lower and the average relative-phase values are increasing. One reason for this is that the submarine was located at a slightly greater range during 17 to 25 February. Another reason (as we shall see) is that the daytime attenuation rate has changed.

Presented in table 5 are the February 1978 North-Atlantic-area average field strengths during specific time periods. The average range from WTF was 4.2 Mm from 1 to 12 February, 3.9 Mm from 14 to 16 February, 4.4 Mm from 17 to 19 February, and 4.5 Mm from 20 to 26 February.

As was previously mentioned, the average February 1978 North-Atlantic-area measured field strengths are identical to the 4.25 Mm predicted values, which are based on attenuation rates and excitation factors inferred from previous PVS measurements. Referring to table 5, we see that the average measured nighttime field strengths at ranges of 3.9, 4.2, 4.4, and 4.5 Mm were -152.1, -152.6, -153.2, and -153.1 dBA/m, respectively. Based on the previously mentioned values of nighttime attenuation rate (0.9 dB/Mm) and

excitation factor (-3.8 dB), the predicted nighttime field strengths at these four ranges are -152.0, -152.6, -153.0, and -153.1 dBA/m, respectively, which are in excellent agreement with the measured nighttime field strengths.

Referring again to table 5, we see that the average measured daytime field-strength values at ranges of 3.9, 4.2, 4.4, and 4.5 Mm are -150.4, -150.3, -151.8, and -153.5 dBA/m, respectively. Based on the previously mentioned values of daytime attenuation rate (1.25 dB/Mm) and excitation factor (-1.0 dB), the predicted daytime field strengths at these four ranges are -150.6, -151.2, -151.7, and -151.9 dBA/m, respectively. Note that the 14 to 19 February predicted daytime field strengths (at 3.9 and 4.4 Mm) are in excellent agreement with the measured field strengths. However, the 1 to 12 February measured daytime field strengths (at 4.2 Mm) are -1 dB higher than predicted, while the 20 to 25 February measured daytime field strengths (at 4.5 Mm) are -1.5 dB lower than predicted.

As we previously noted, the Connecticut daytime field strengths measured from 3 to 12 February were -1 dB greater than those measured from 20 to 26 February (see table 2). The fact that the difference between the 1 to 12 and 20 to 26 February measured values is greater in the North Atlantic than in Connecticut suggests a change in the daytime attenuation rate rather than a change in the daytime excitation factor.

A comparison of the measured and predicted February 1978 Connecticut and North-Atlantic-area daytime field strengths is presented in table 6. The 14 to 19 February field-strength predictions are based on the monthly average values of attenuation rate (1.25 dB/Mm) and excitation factor (-1.0 dB).

The 1 to 12 February daytime predictions assume an attenuation rate of only 1 dB/Mm (0.25 dB/Mm less than the monthly average) and an excitation factor of -1.1 dB. The 20 to 25 February predictions assume an attenuation rate of 1.5 dB/Mm (0.25 dB/Mm more than the monthly average) and excitation factor of -1.3 dB. Referring to table 6, we see that the agreement between the predicted and measured Connecticut and North-Atlantic-area daytime field strengths is excellent during each of the four time periods.

The short-lived low-energy solar-particle event of 25 February also appeared to affect ELF daytime propagation. However, this is not conclusive, since no Connecticut data were obtained on 24 February and no North-Atlantic-area data were obtained after 25 February. Nonetheless, the 25 February 1800 to 2000 North-Atlantic-area daytime field strengths were -3.5 dB less than those measured on 24 February (see appendix B) and the 25 February 1600 to 2000 daytime field strengths were 0.5 to 2 dB less than those measured during the next three days (see figures 9 and 10).

## CONCLUSIONS

The average measured field strengths (both amplitude and relative phase) taken aboard two submarines, one located in the North-Atlantic area and one located in the Western-Pacific area, during January/February 1978 are in excellent agreement with simultaneous measurements taken in Connecticut and with previous measurements taken over similar paths.

ELF propagation effects were also observed before, during, and after the 13 February 1978 significant solar-particle event at both the Connecticut and North-Atlantic-area locations. When the PCA started (3 hr before WTF sunrise), the North-Atlantic-area relative phase immediately dropped to the daytime level and remained there for 2 days (which infers a decrease in the nighttime reflection height of 25 to 30 km). Meanwhile, the Connecticut relative-phase variation was near normal.

Based on an analysis of both the Connecticut and North-Atlantic-area daytime field strengths, it appears that the daytime attenuation rate was  $-1.0$  dB/Mm before the event,  $-1.25$  dB/Mm for 6 days after the event, and  $-1.5$  dB/Mm for 7 to 12 days after the event. However, the daytime excitation factor only varied by 0.1 to 0.3 dB.

Table 1. January 1978 North-Atlantic-Area Submarine Daily Field-Strength Averages

Date	Night $H_{\phi}$ (dBA/m)	SRTP $H_{\phi}$ (dBA/m)	Day $H_{\phi}$ (dBA/m)	SSTP $H_{\phi}$ (dBA/m)	Relative Phase (deg)
12/31	-154.3	-154.7	-153.6	-151.1	68
1/1	-155.9	-155.8	-154.0	-152.0	78
1/21	-153.9	-152.5	-152.2	-151.5	60
1/22	-155.1	-153.1	-152.5	-152.0	23
1/24	-155.0	-153.1	-152.3	-153.3	68
1/25	-154.7	-153.8	-152.3	-152.1	100
1/26	-155.8	-153.3	-151.9	-154.4	68
1/27	-155.9	-154.2	-153.3	-153.3	64
1/28	-154.8	-152.5	-152.2	-152.4	75
1/29	-153.2	-152.5	-151.5	-152.7	50
1/30	-153.3	-152.3	-150.8	-153.0	62
1/31	-152.4	-152.1	-151.0	-152.2	47
Monthly Averages	-154.5	-153.3	-152.3	-152.5	64

Table 2. February 1978 Connecticut Daily Field-Strength Averages

Date	Day $H_{\phi}$ (dBA/m)	SSTP $H_{\phi}$ (dBA/m)	Night $H_{\phi}$ (dBA/m)	SRTP $H_{\phi}$ (dBA/m)	$\Delta\phi$ (deg)
2/2-2/3	-142.9	-143.9	-145.6	-144.1	16
2/4-2/5	-143.0	-144.1	-145.4	-143.7	17
2/5-2/6	-142.9	-143.7	-144.4	-143.7	14
2/10-2/11	-143.0	-143.9	-145.6	-144.6	20
2/11-2/12	-143.0	-144.3	-145.1	-144.4	20
2/12-2/13	-143.1	-	-145.8	-144.8	18
2/13-2/14	-143.1	-143.5	-146.3	-144.9	20
2/14-2/15	-143.3	-144.0	-146.2	-144.2	15
2/17-2/18	-143.2	-144.1	-145.4	-144.7	26
2/18-2/19	-143.6	-144.2	-145.7	-144.6	20
2/19-2/20	-144.0	-144.3	-145.9	-145.0	22
2/20-2/21	-143.8	-144.4	-146.3	-145.0	24
2/21-2/22	-143.7	-143.7	-146.4	-144.3	21
2/22-2/23	-144.2	-144.0	-145.6	-144.4	20
2/24-2/25	-144.2	-144.1	-145.9	-145.0	16
2/25-2/26	-143.9	-144.7	-146.0	-144.5	16
2/26-2/27	-143.6	-144.0	-146.1	-144.4	19
2/27-2/28	-143.1	-143.3	-145.8	-144.1	18
Monthly Average	-143.4	-144.0	-145.8	-144.4	19

Table 3. February 1978 North-Atlantic-Area Submarine  
Daily Field-Strength Averages

Date	Night $H_{\phi}$ (dBA/m)	SRTP $H_{\phi}$ (dBA/m)	Day $H_{\phi}$ (dBA/m)	SSTP $H_{\phi}$ (dBA/m)	Relative Phase (deg)
1/31-2/1	-152.8	-151.3	-150.9	-152.3	53
2/1-2/2	-153.1	-151.6	-150.6	-151.5	48
2/2-2/3	-152.6	-151.0	-149.9	-	48
2/4-2/5	-151.7	-151.5	-149.6	-152.3	60
2/5-2/6	-152.0	-152.3	-150.0	-151.3	58
2/6-2/7	-152.2	-151.8	-151.2	-152.1	62
2/7-2/8	-153.1	-151.1	-150.3	-153.1	58
2/8-2/9	-153.5	-151.8	-	-152.8	62
2/9-2/10	-154.0	-151.4	-150.2	-	59
2/10-2/11	-151.8	-150.5	-149.8	-153.1	63
2/11-2/12	-152.4	-151.8	-151.1	-150.4	88
2/12-2/13	-152.0	-151.7	-150.1	-	56
2/13-2/14	-152.5	-153.3	-150.2	-150.5	-6
2/14-2/15	-152.3	-150.0	-150.7	-151.0	7
2/15-2/16	-151.7	-152.0	-150.3	-150.2	20
2/16-2/17	-152.5	-151.9	-151.1	-149.9	41
2/17-2/18	-153.3	-152.7	-151.2	-151.5	65
2/18-2/19	-154.0	-153.3	-153.1	-153.4	66
2/19-2/20	-152.3	-153.0	-152.4	-	60
2/20-2/21	-153.0	-153.0	-153.5	-152.5	77
2/21-2/22	-153.0	-153.0	-153.5	-151.3	83
2/22-2/23	-152.3	-152.5	-153.8	-152.7	88
2/23-2/24	-154.2	-153.1	-152.9	-152.9	64
2/24-2/25	-154.0	-153.9	-154.2	-152.0	57
Monthly Average	-152.7	-152.0	-151.3	-151.9	56

Table 4. 1977-78 North-Atlantic-Area Average Field Strengths  
(Normalized to  $F(\phi)/B = 1.0$ )

Time	January 1977 $H_\phi$ (dBA/m)	March 1977 $H_\phi$ (dBA/m)	April 1977 $H_\phi$ (dBA/m)	October 1977 $H_\phi$ (dBA/m)	January 1978 $H_\phi$ (dBA/m)	February 1978 $H_\phi$ (dBA/m)	1977-78 Average $H_\phi$ (dBA/m)
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
SRTP	-153.5	-151.7	-151.8	-151.8	-153.3	-152.0	-152.3
Total 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

Table 5. February 1978 North-Atlantic-Area Average  
Field Strengths During Specific Periods

Time	2/1-2/12 $H_\phi$ (dBA/m)	2/14-2/16 $H_\phi$ (dBA/m)	2/17-2/19 $H_\phi$ (dBA/m)	2/20-2/25 $H_\phi$ (dBA/m)	Average $H_\phi$ (dBA/m)
Day	-150.3	-150.4	-151.8	-153.3	-151.3
SSTP	-152.1	-150.5	-151.6	-152.3	-151.9
Night	-152.6	-152.1	-153.2	-153.1	-152.7
SRTP	-151.4	-151.7	-152.6	-153.0	-152.0
Total TP	-151.7	-151.1	-152.1	-152.6	-152.0
$\Delta\phi$ (deg)	60	7	57	71	56
Average Distance (Mm)	4.2	3.9	4.4	4.5	4.25
$\Delta(c/v)$	0.16	0.02	0.14	0.17	0.14

Table 6. Comparison of Measured and Predicted February 1978  
Connecticut and North-Atlantic  
Daytime Field Strengths

Date	Location	Range (Mm)	Measured $H_{\phi}$ (dBA/m)	Predicted $H_{\phi}$ (dBA/m)
2/1-2/12	North Atlantic	4.2	-150.3	-150.3
2/1-2/12	Connecticut	1.6	-143.0	-143.0
2/14-2/16	North Atlantic	3.9	-150.4	-150.6
2/14-2/15	Connecticut	1.6	-143.2	-143.3
2/17-2/19	North Atlantic	4.4	-151.8	-151.7
2/18-2/19	Connecticut	1.6	-143.4	-143.3
2/20-2/25	North Atlantic	4.5	-153.3	-153.3
2/20-2/26	Connecticut	1.6	-144.0	-144.0



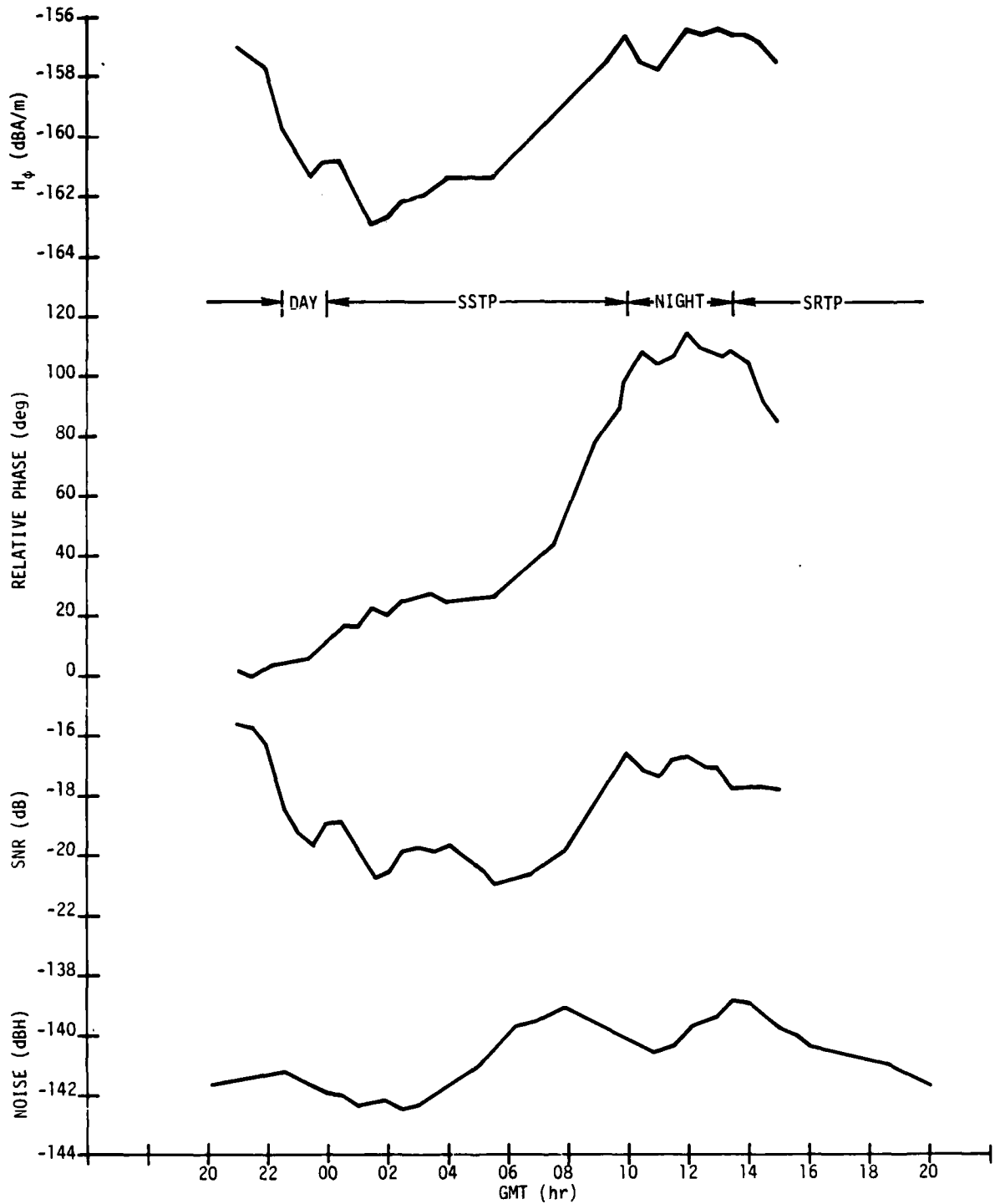


Figure 1. January 1978 Western-Pacific-Area Average Data Versus GMT ( $\psi = 291$  deg)

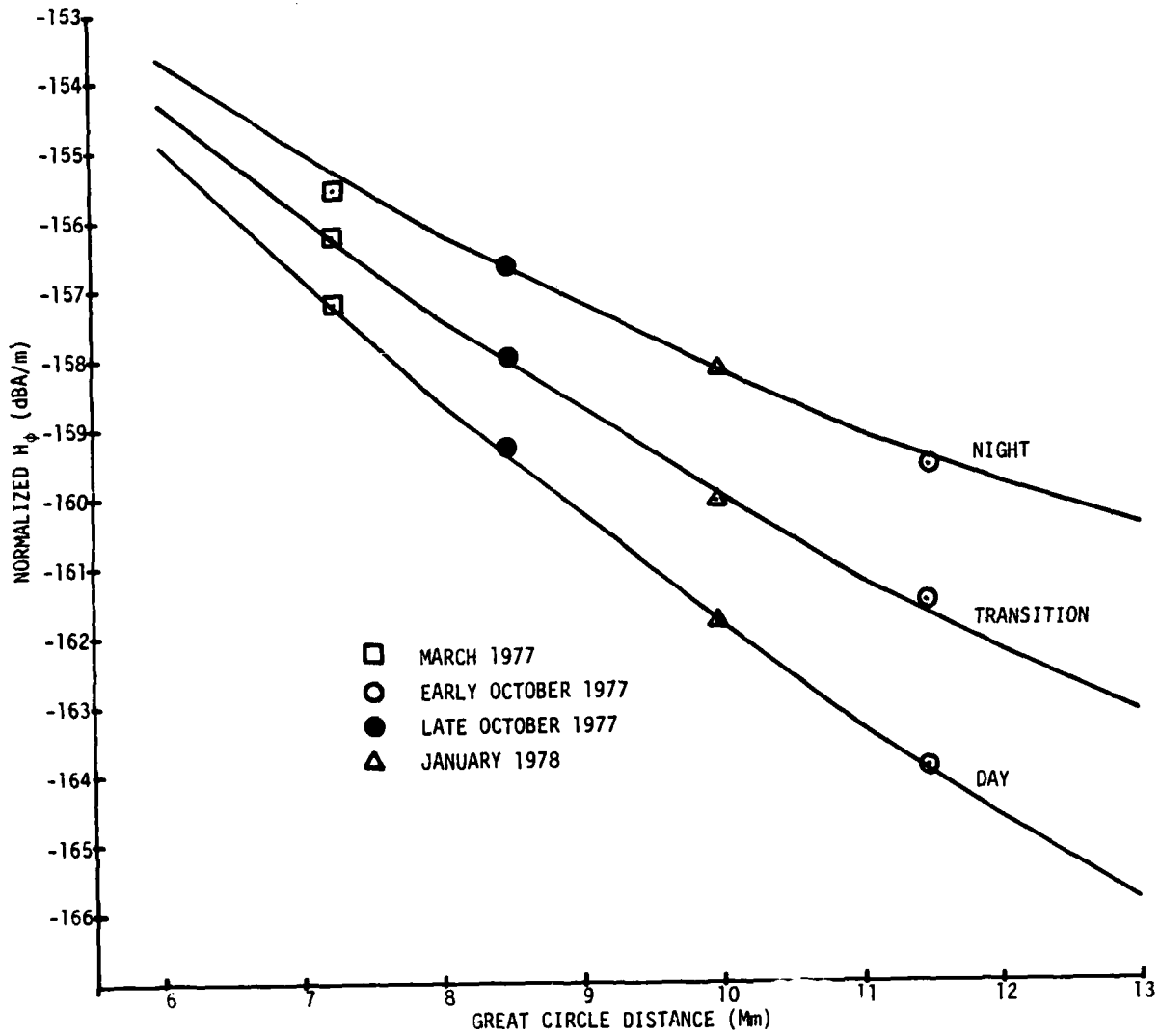


Figure 2. Comparison of 1977-78 Western-Pacific-Area Predicted and Measured Field Strengths

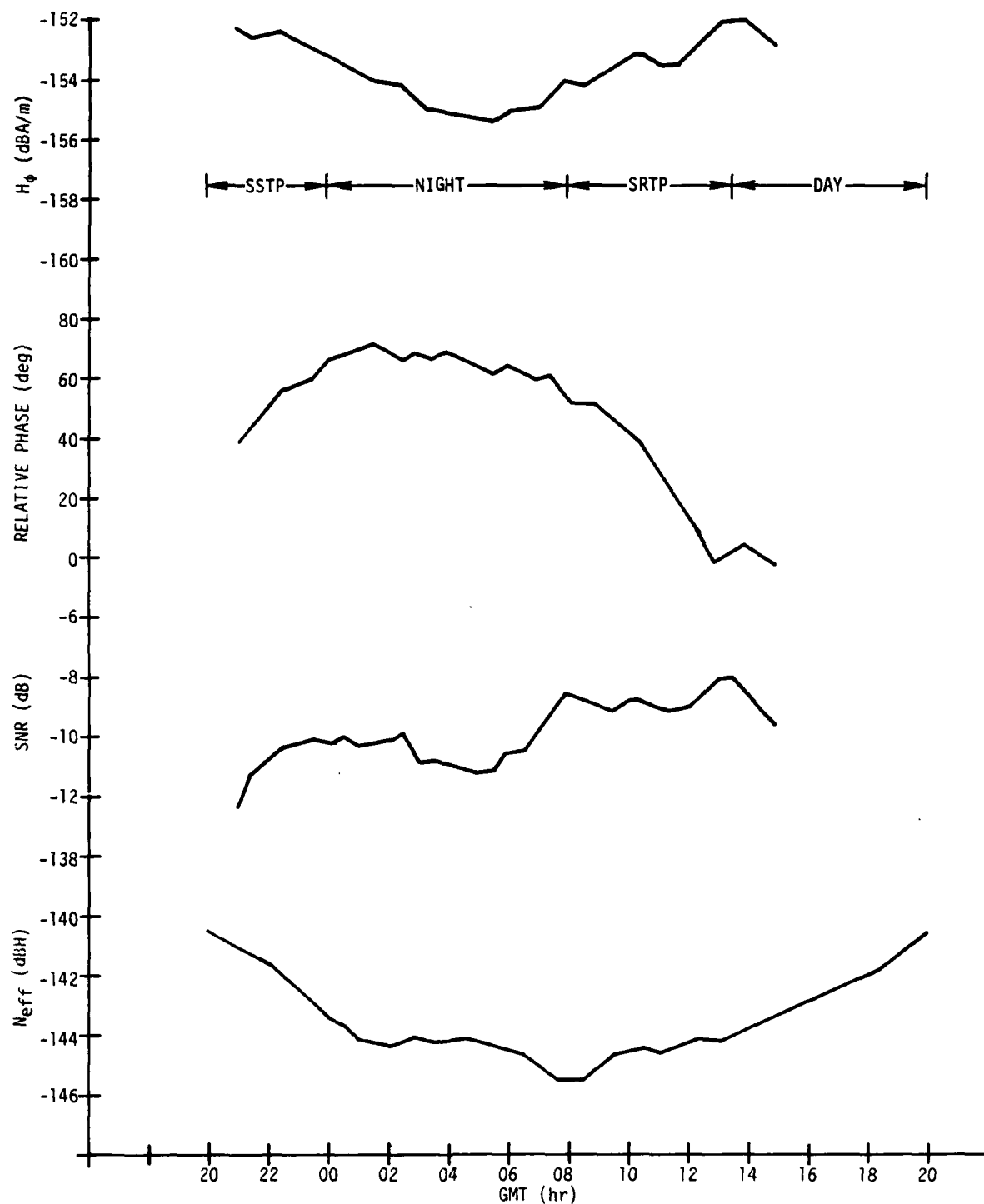


Figure 3. January 1978 North-Atlantic-Area Average Data Versus GMT ( $\psi = 291$  deg)

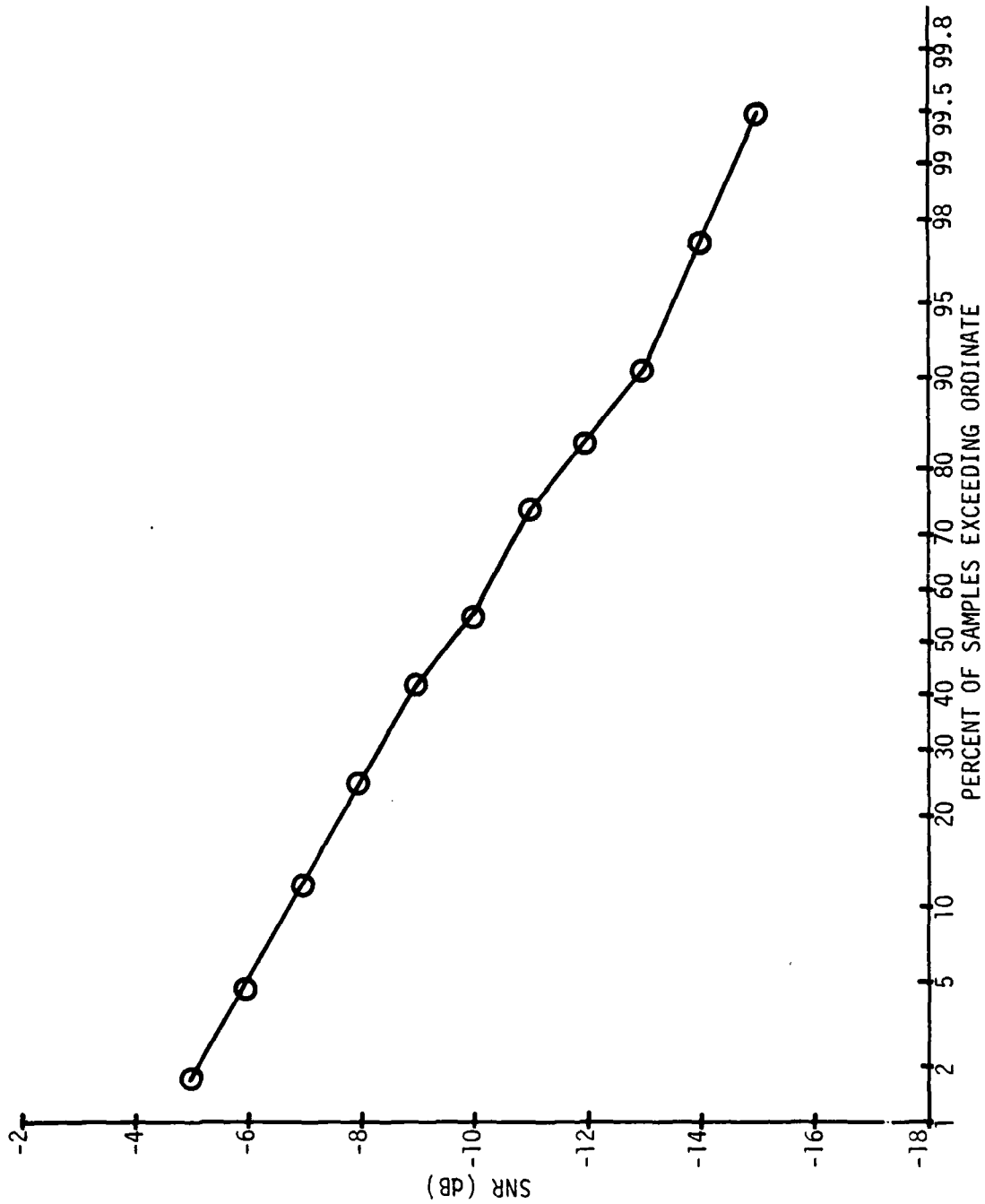


Figure 4. January 1978 North-Atlantic-Area SNR Distribution (N = 410)

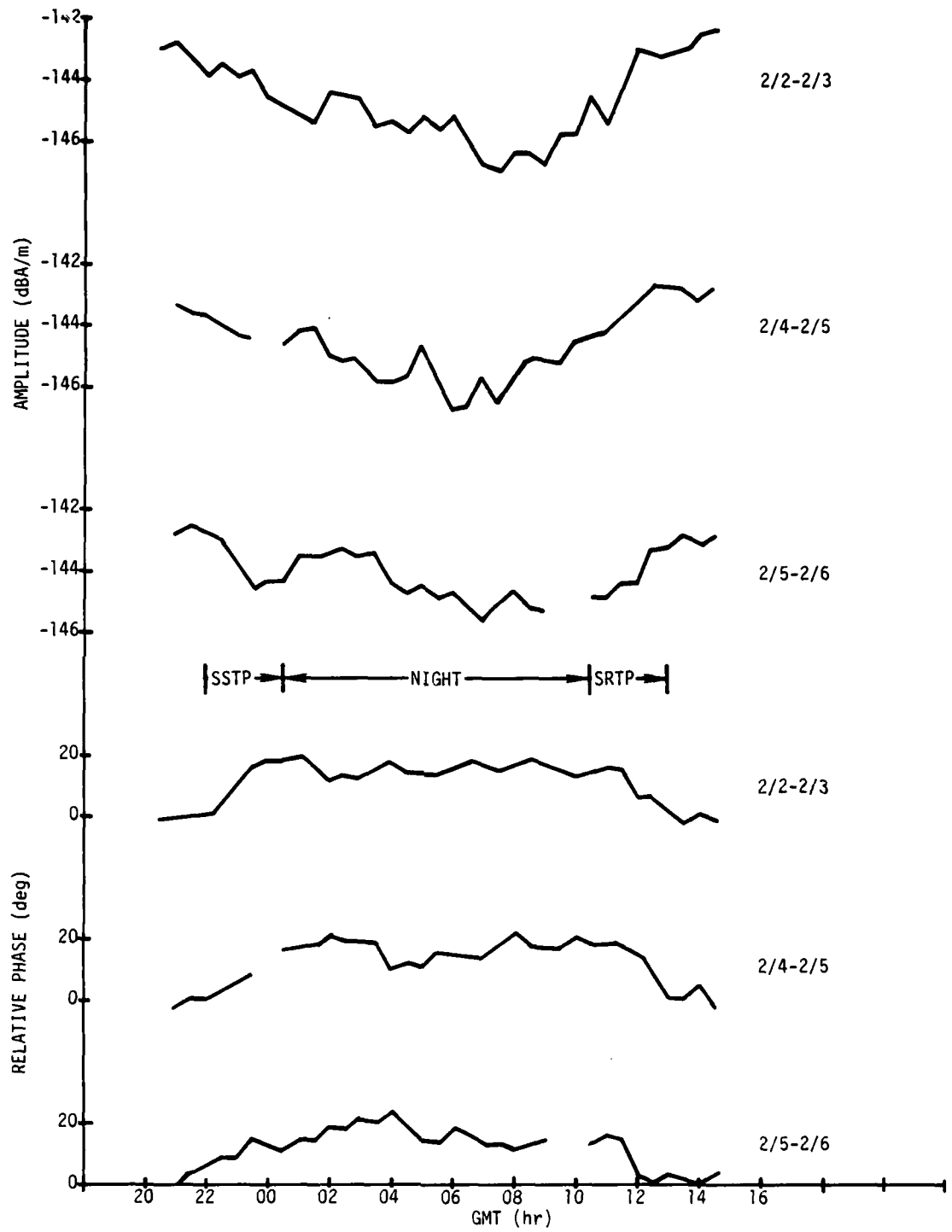


Figure 5. Connecticut Field Strength Versus GMT, 3 to 6 February 1978

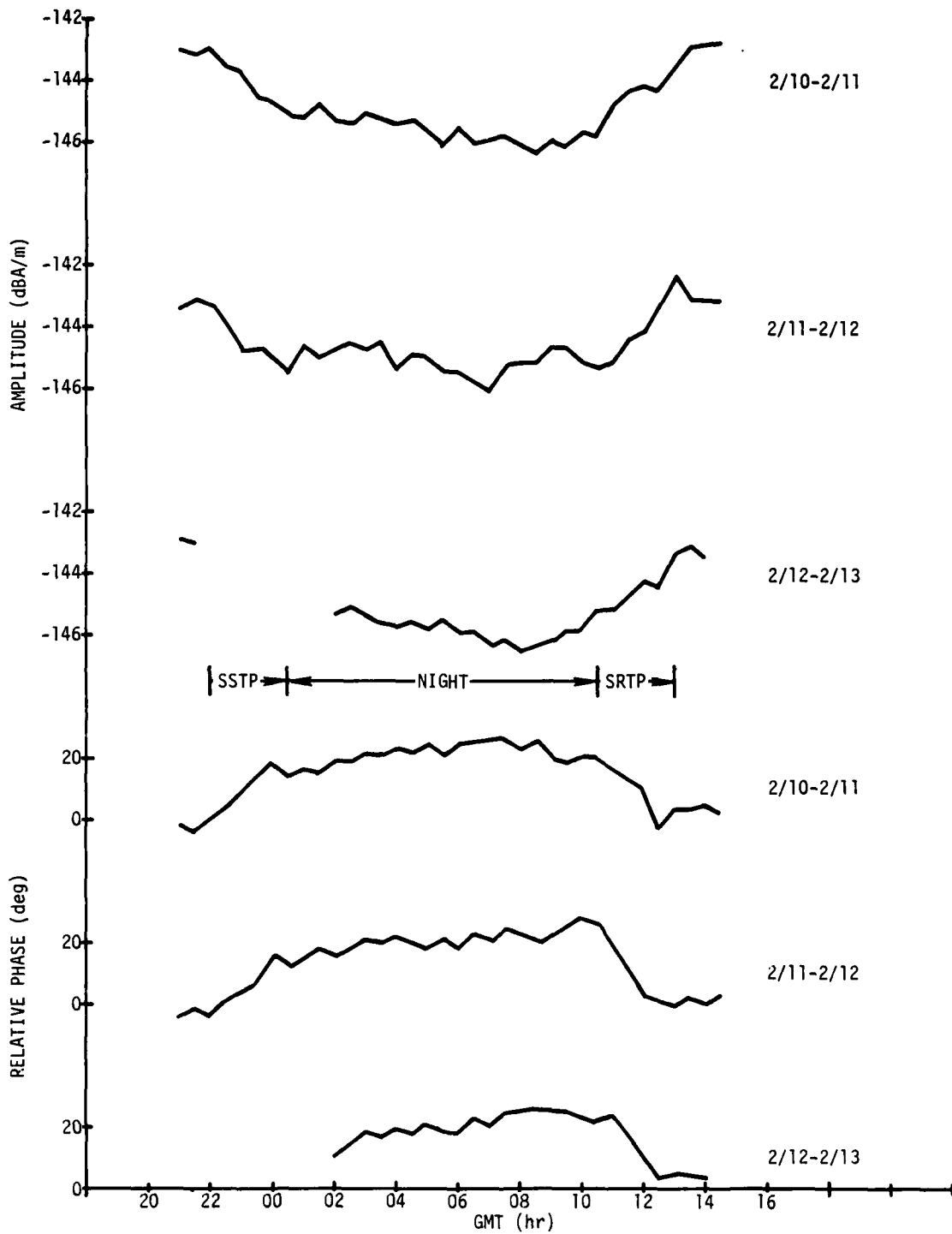


Figure 6. Connecticut Field Strength Versus GMT, 11 to 13 February 1978

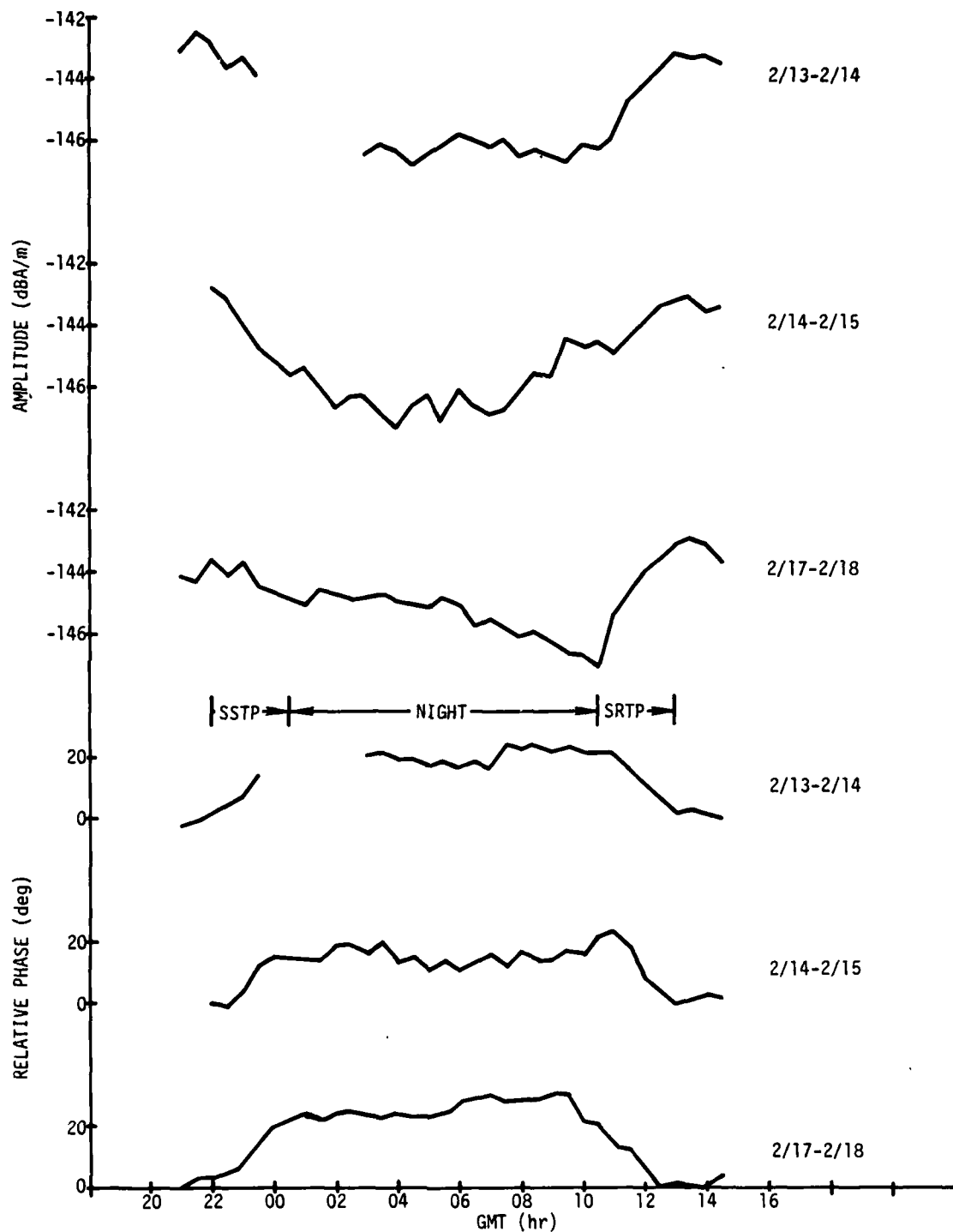


Figure 7. Connecticut Field Strength Versus GMT, 14 to 18 February 1978

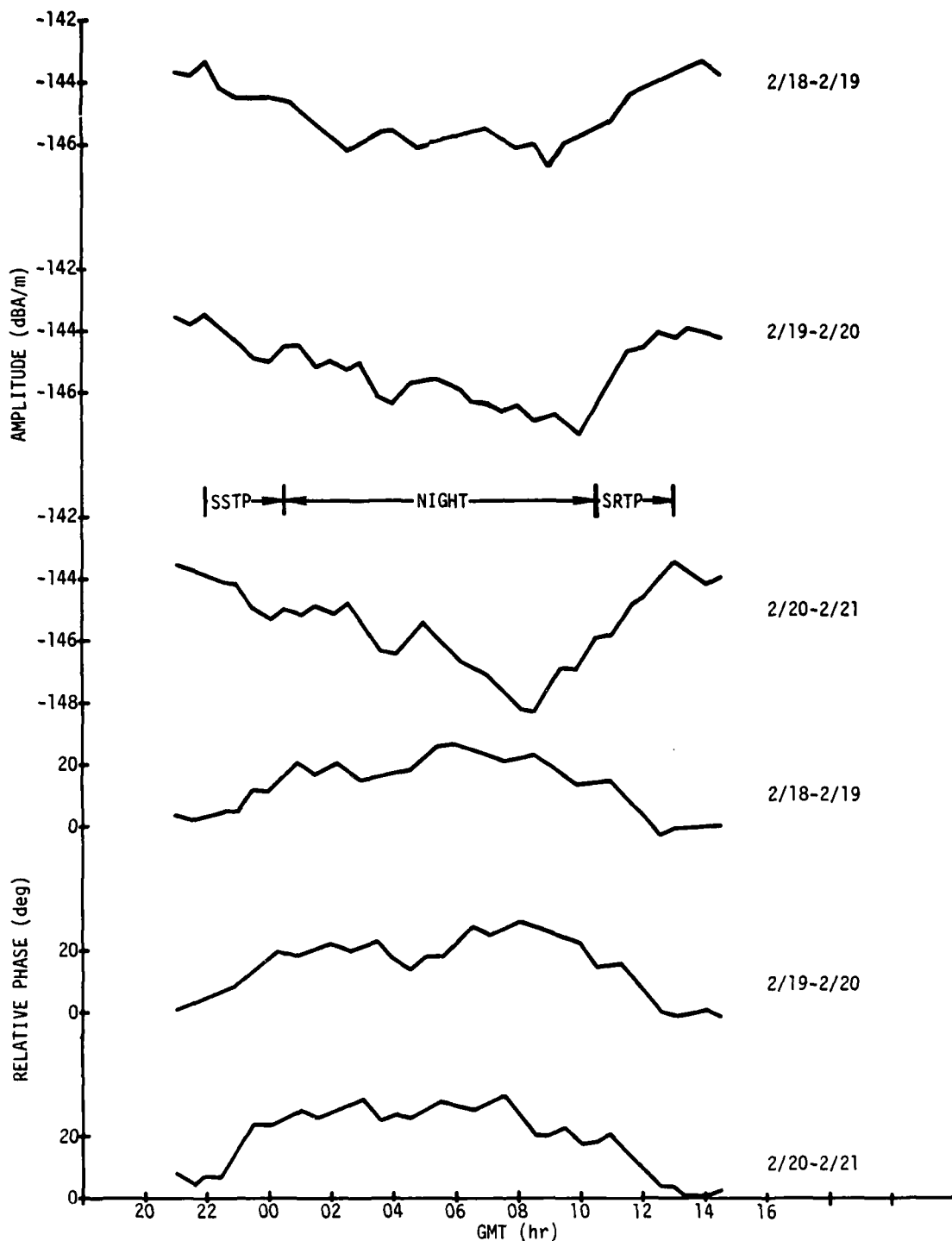


Figure 8. Connecticut Field Strength Versus GMT, 19 to 21 February 1978



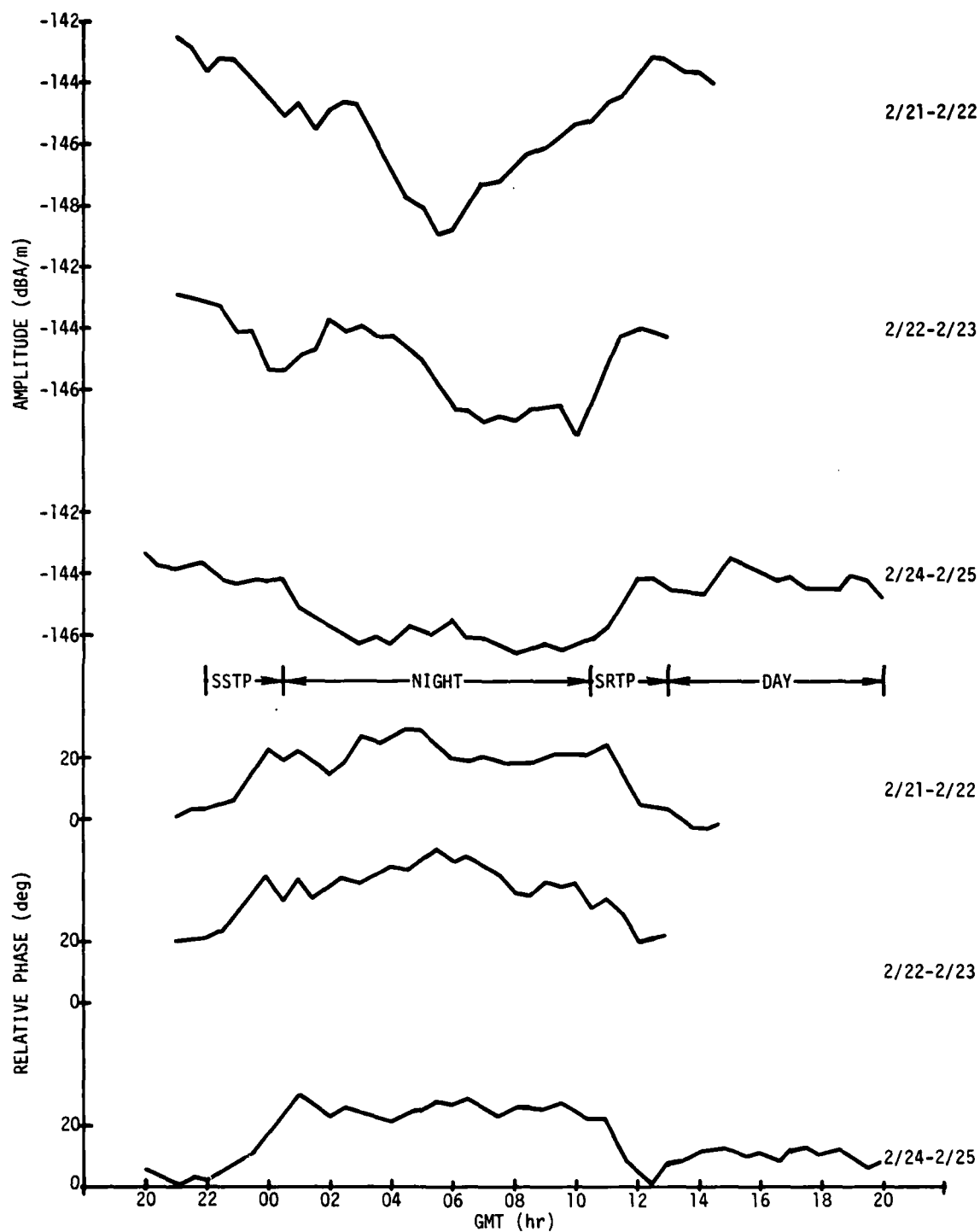


Figure 9. Connecticut Field Strength Versus GMT, 22 to 25 February 1978

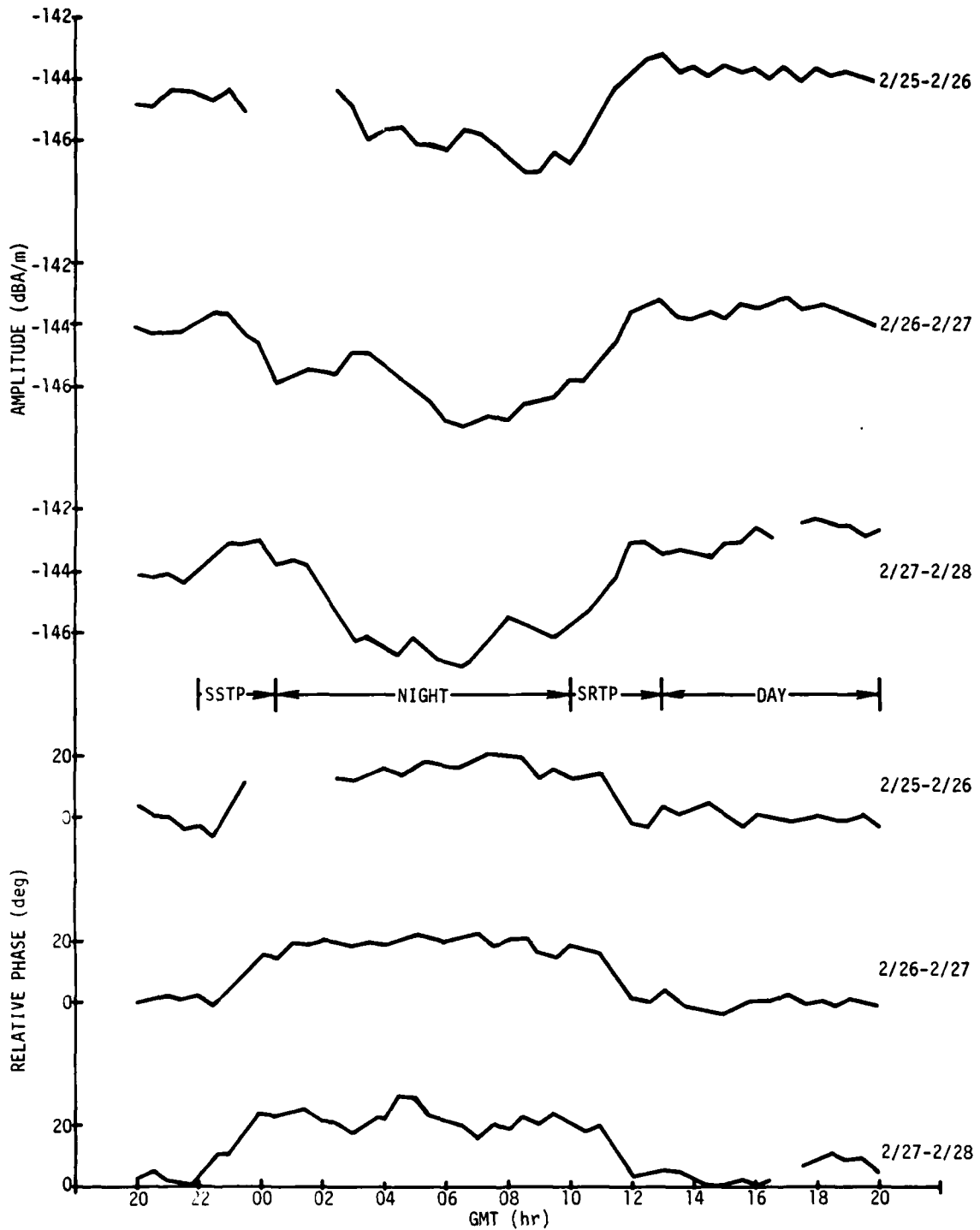


Figure 10. Connecticut Field Strength Versus GMT, 26 to 28 February 1978

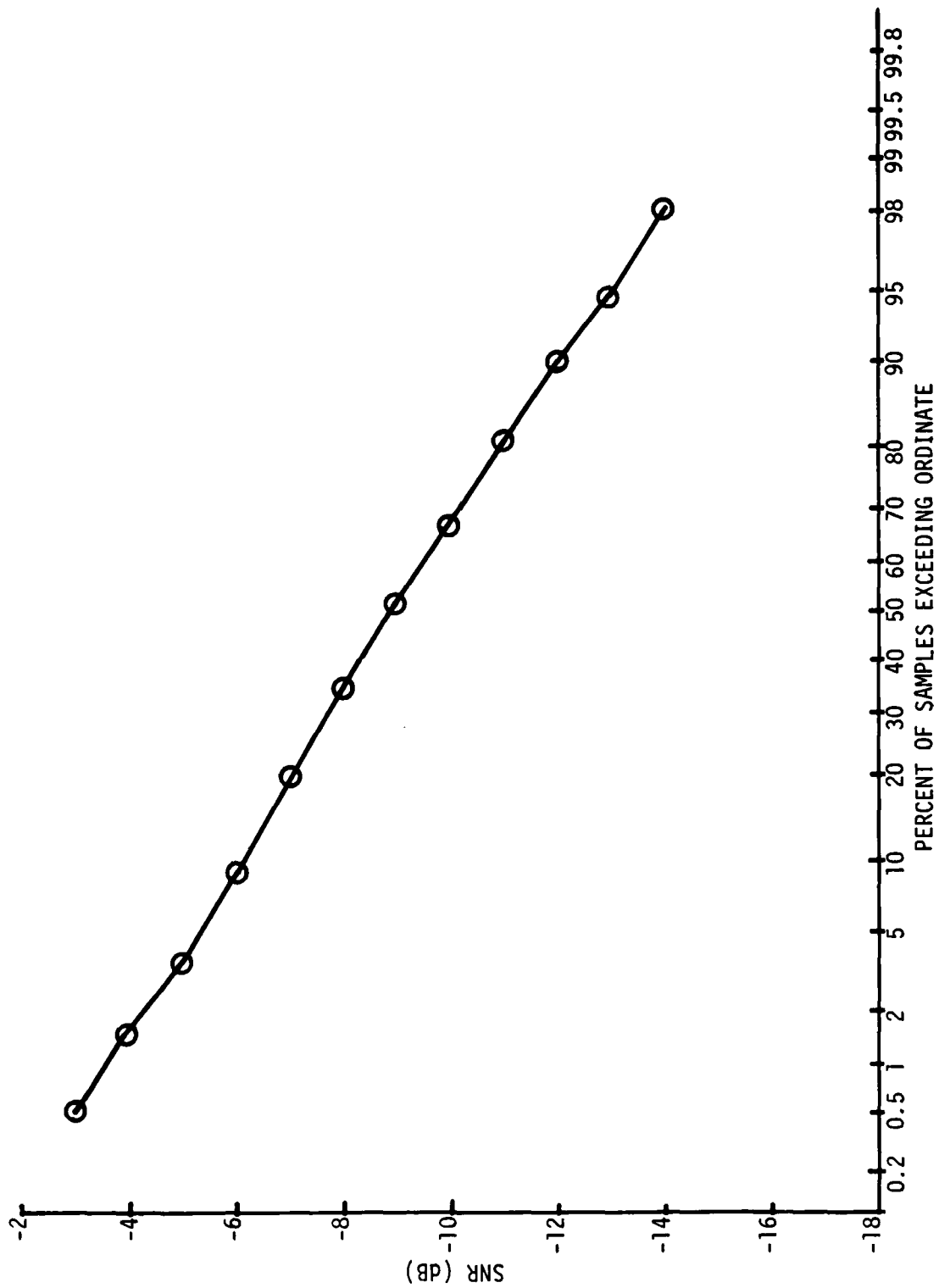


Figure 11. February 1978 North-Atlantic-Area SNR Distribution (N = 805)

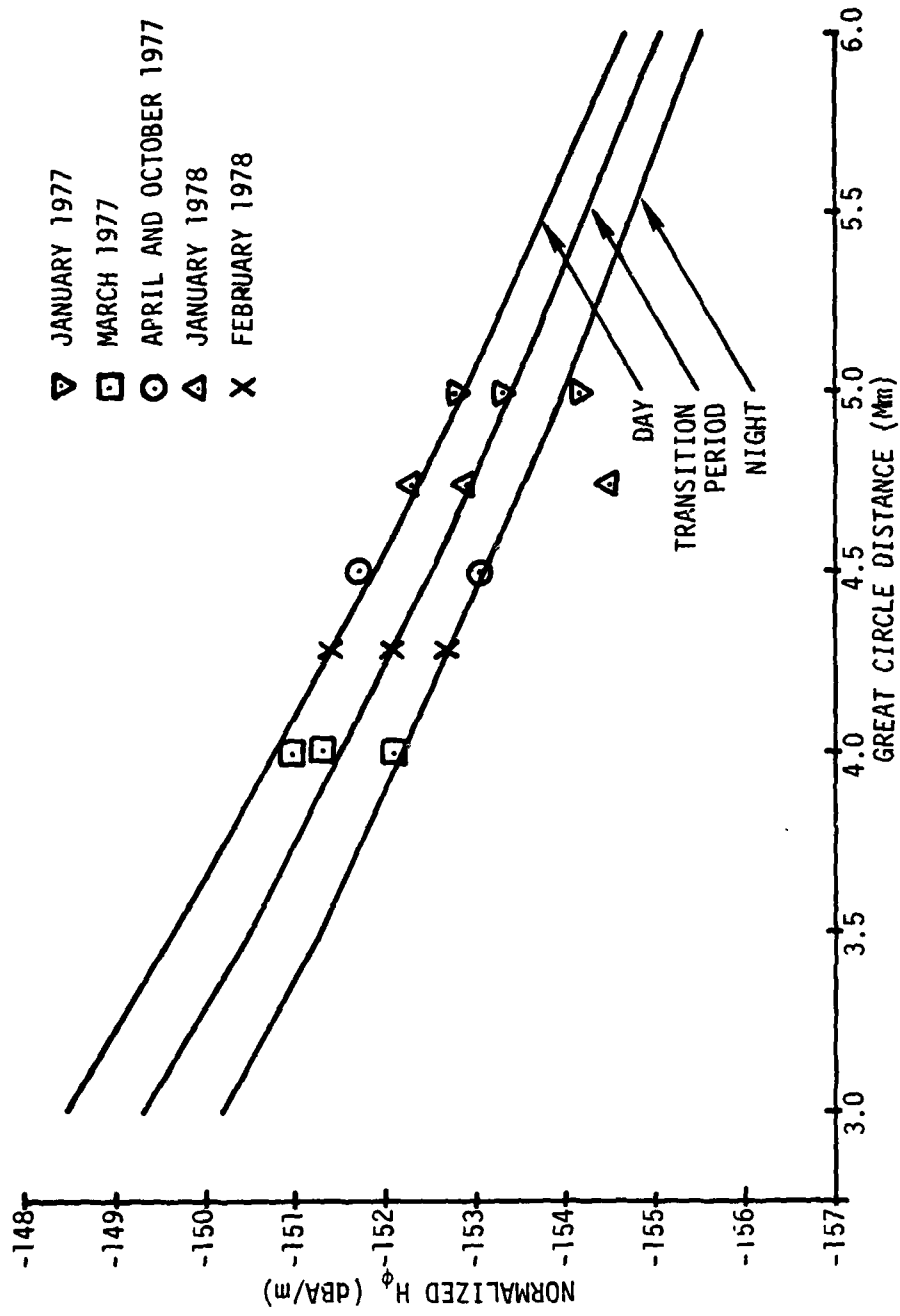


Figure 12. Comparison of 1977-78 North-Atlantic-Area Predicted and Measured Field Strengths

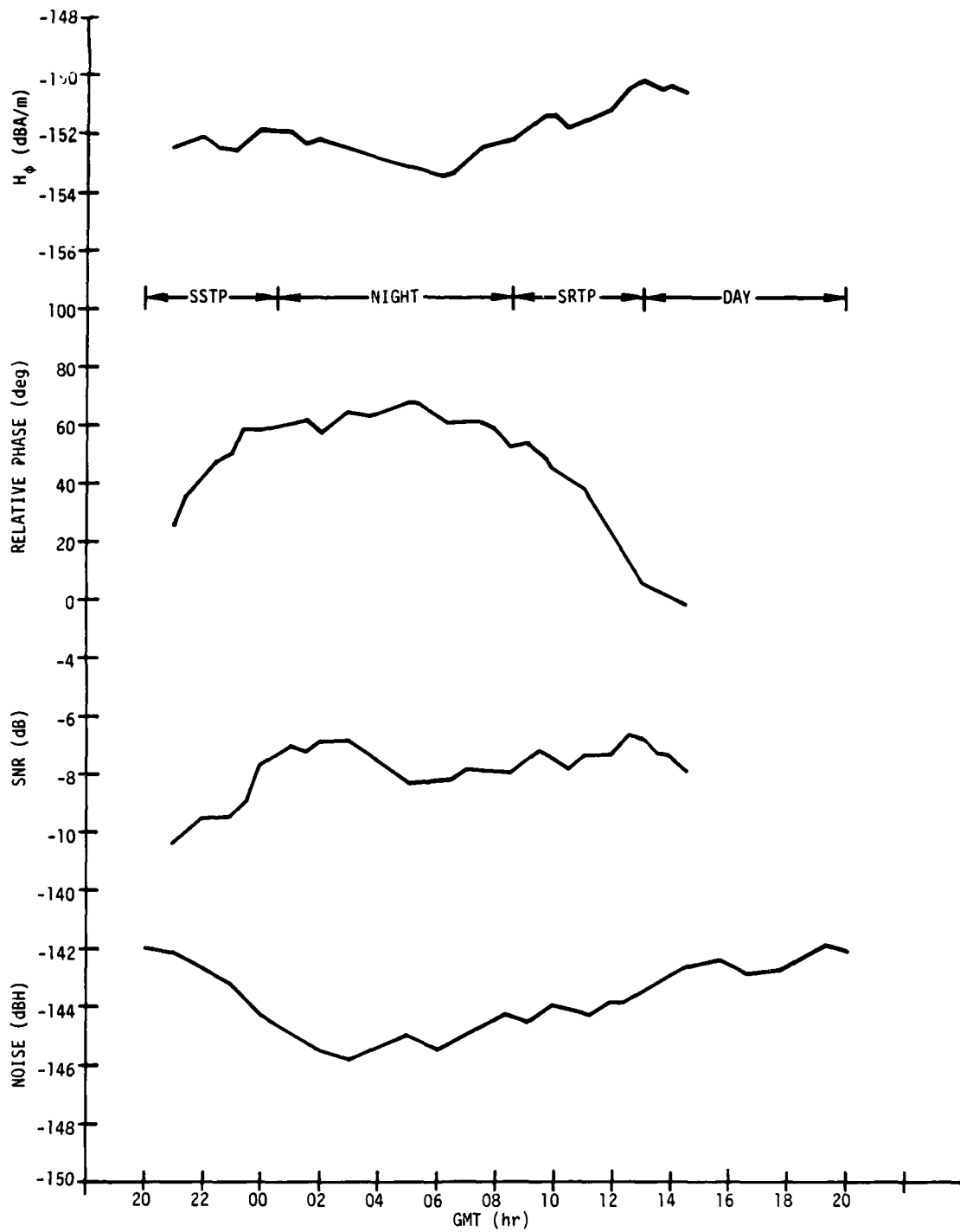


Figure 13. North-Atlantic-Area Average Data Versus GMT ( $\psi = 291$  deg), 1 to 12 February 1978

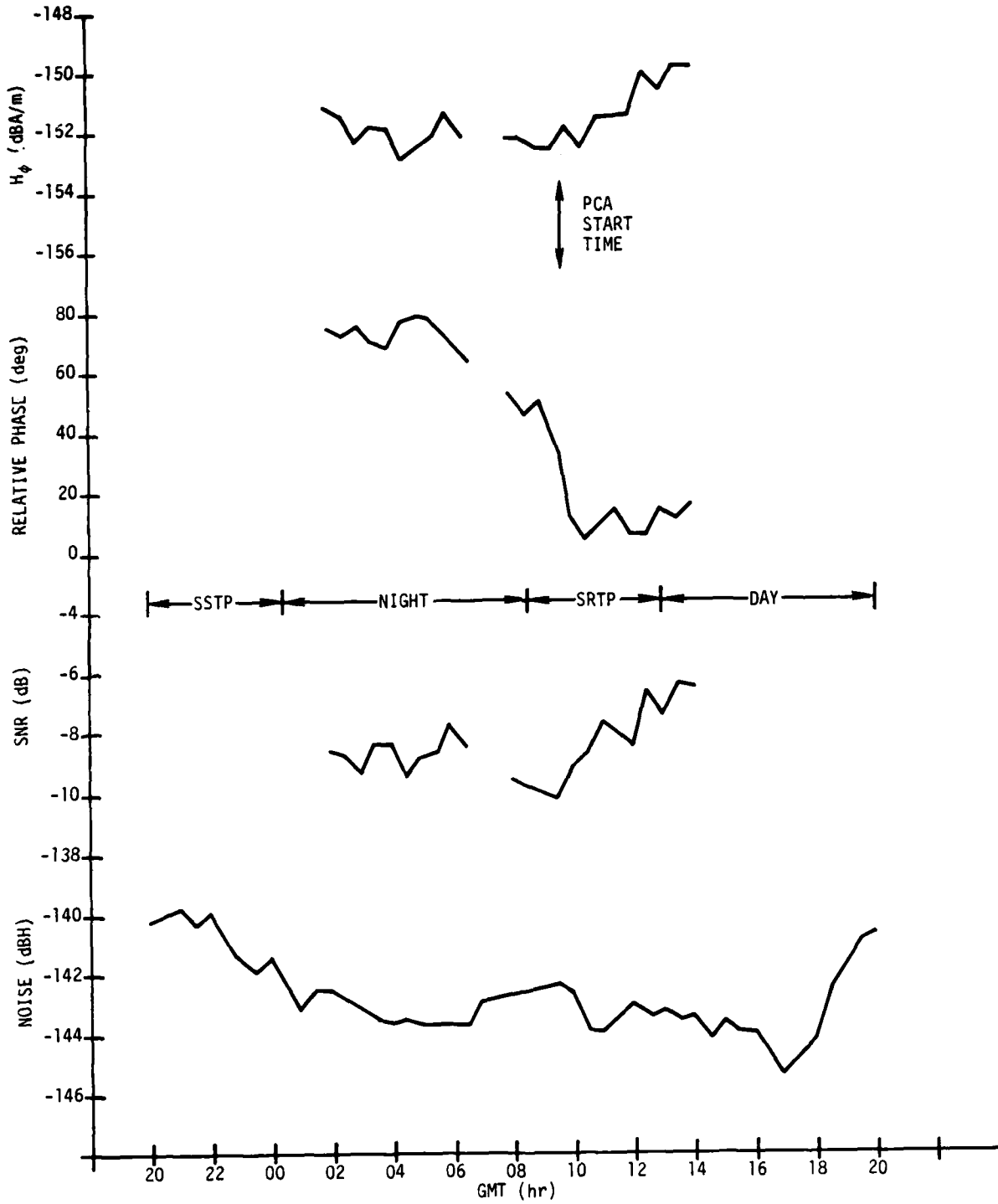


Figure 14. North-Atlantic-Area Average Data Versus GMT ( $\psi = 291$  deg), 13 February 1978

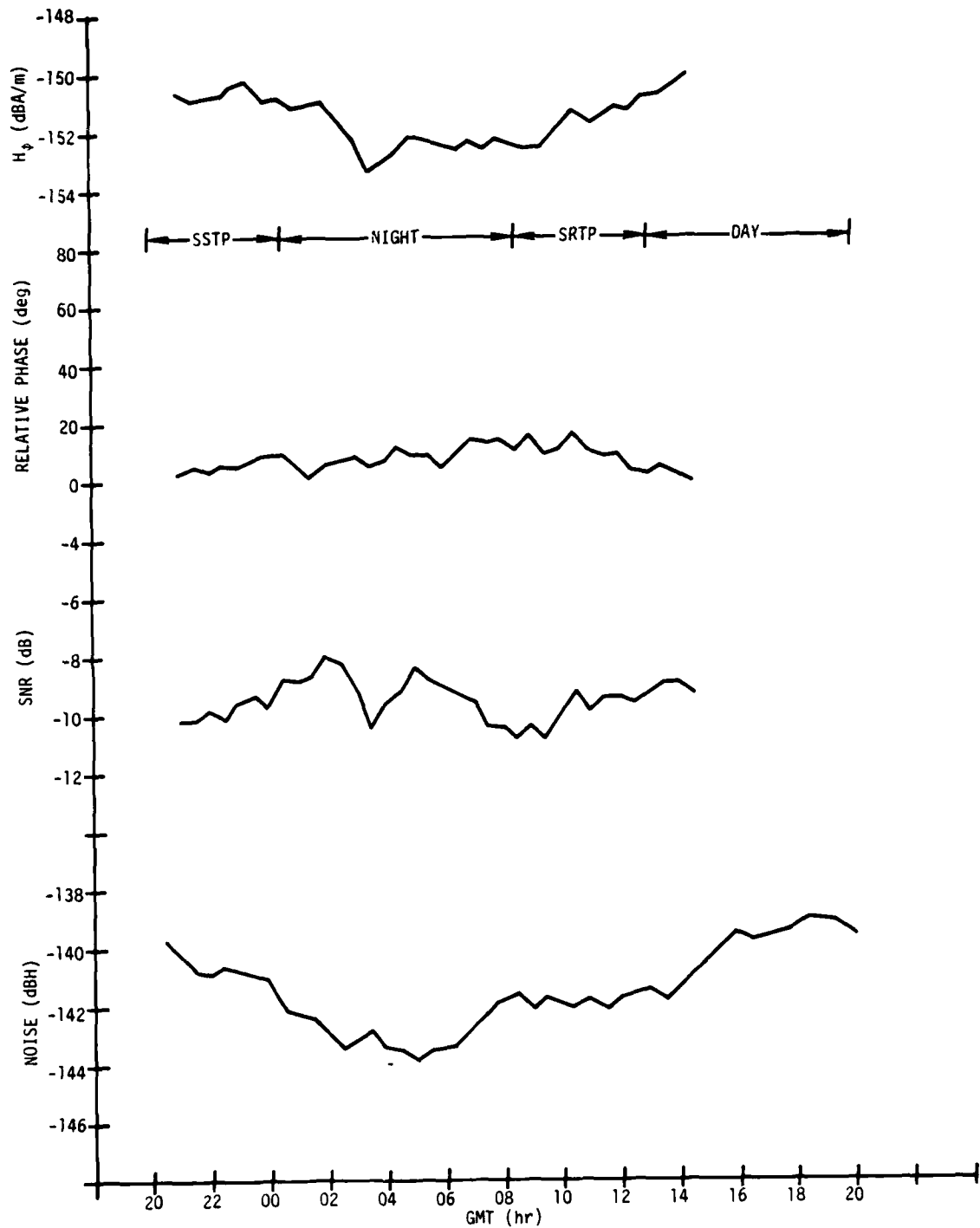


Figure 15. North-Atlantic-Area Average Data Versus GMT ( $\psi = 291$  deg), 14 to 16 February 1978

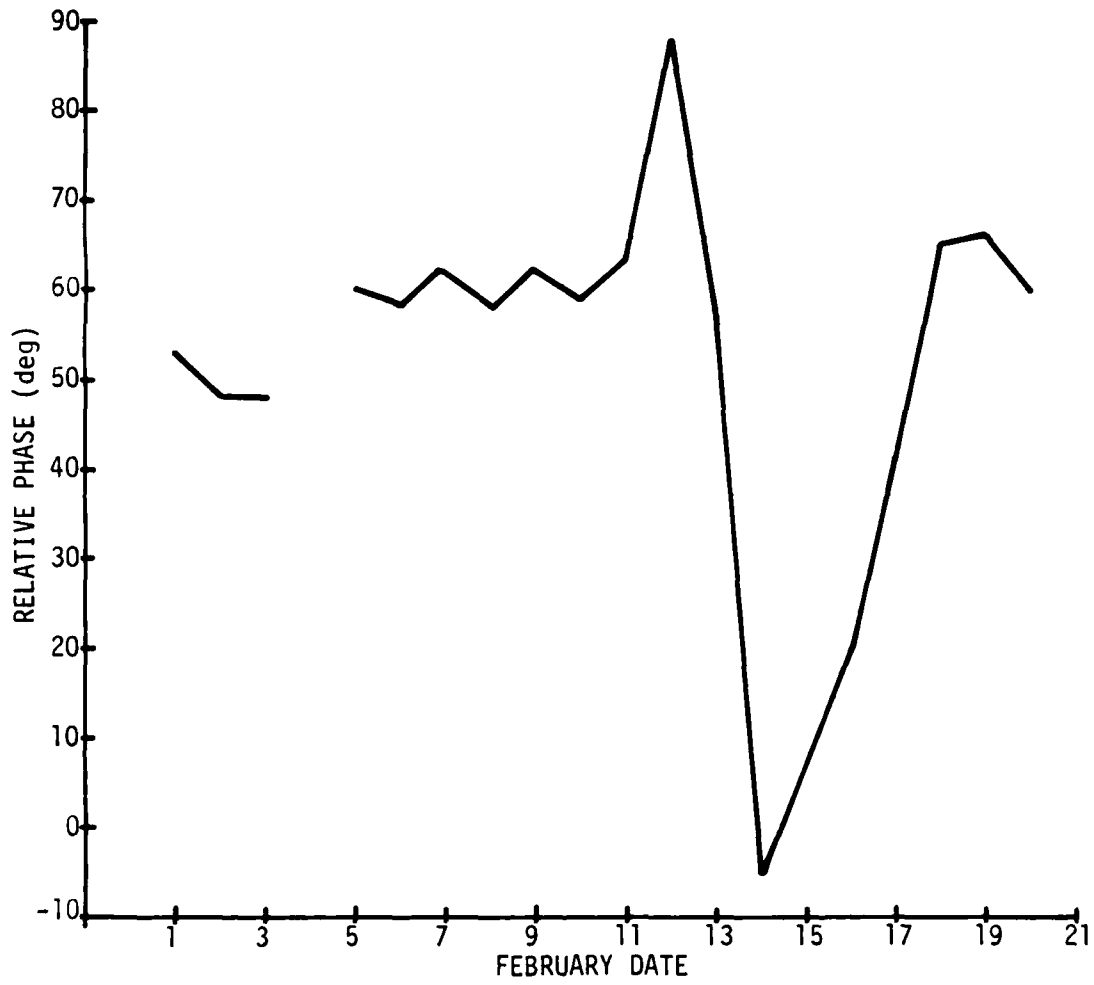


Figure 16. North-Atlantic-Area Daily Average Relative Phase Versus Date, 1 to 20 February 1978



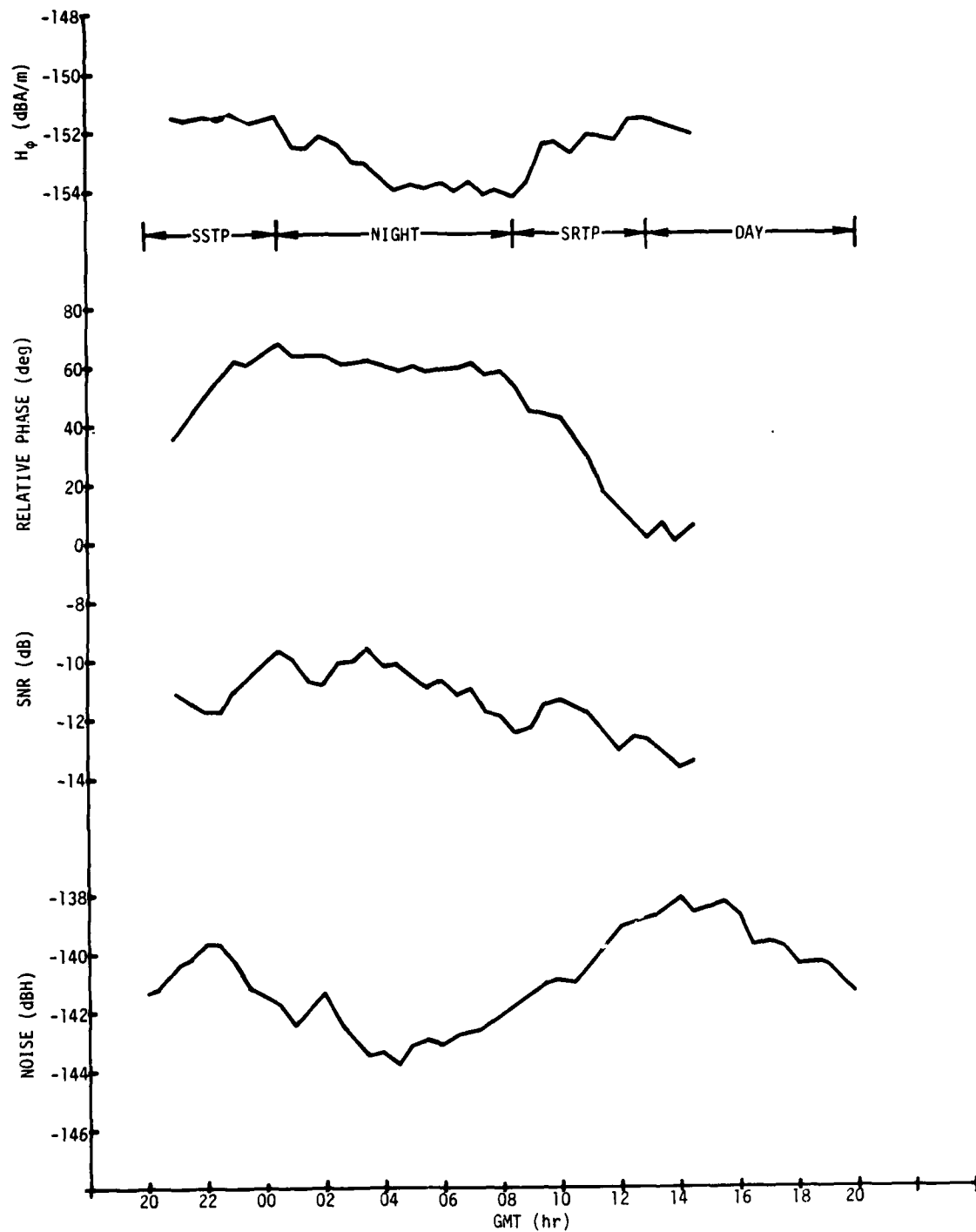


Figure 17. North-Atlantic-Area Average Data Versus GMT ( $\psi = 291$  deg), 17 to 19 February 1978

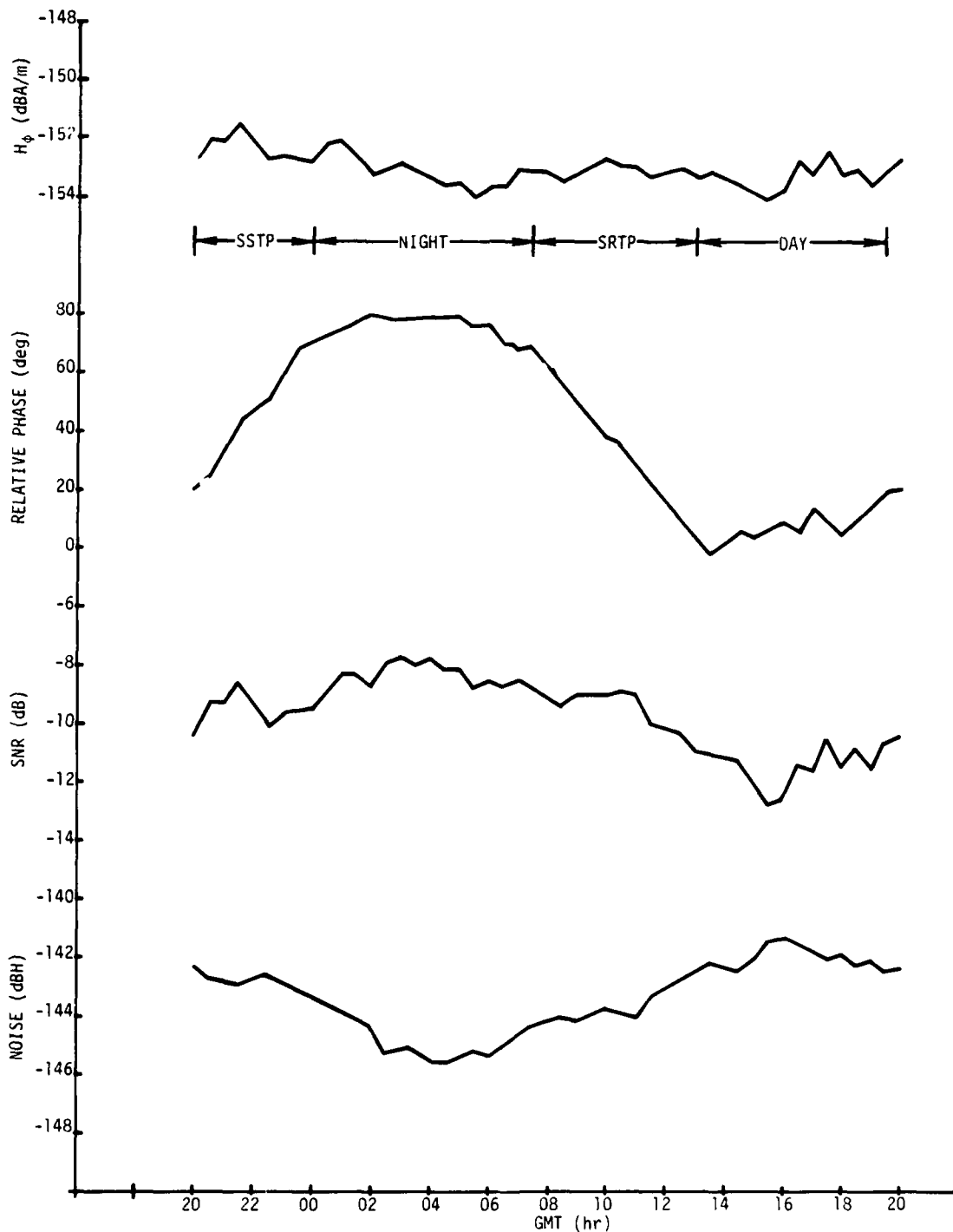


Figure 18. North-Atlantic-Area Average Data Versus GMT ( $\psi = 291$  deg), 20 to 25 February 1978

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## Appendix A

## JANUARY 1978 NORTH-ATLANTIC-AREA SUBMARINE DAILY DATA

During January of 1978, data were obtained on 12 days from the North-Atlantic-area submarine. The daily field-strength (both amplitude and relative phase), effective-noise, and SNR values are plotted versus GMT in figures A-1 through A-12 in this appendix. The WTF antenna phasing angle ( $\psi$ ) was 291 deg and the transmitting frequency was  $76 \pm 4$  Hz.

Amplitude peak-to-trough variations of 6 to 7 dB occurred during 4 of the 12 measurement days (31 December and 1, 22, and 28 January, figures A-1, A-2, A-4, and A-9). The minimum nighttime field strength was usually measured from 0400 to 0800 GMT.

The night-to-day relative-phase variation was  $\sim 64$  deg, with the largest variation (100 deg) occurring on 25 January (figure A-6), and the smallest variation (23 deg) occurring on 22 January (figure A-4).

The largest daily peak-to-trough variations in the effective noise (11 dB) were measured during 1 January (figure A-1), which was also when the largest peak-to-trough amplitude variation ( $\sim 7$  dB) occurred.

It should be noted that all of the submarine effective-noise data presented in this report are contaminated to some degree by submarine-generated noise (external or internal to the submarine). Thus, the effective-noise values presented here are on the high side.

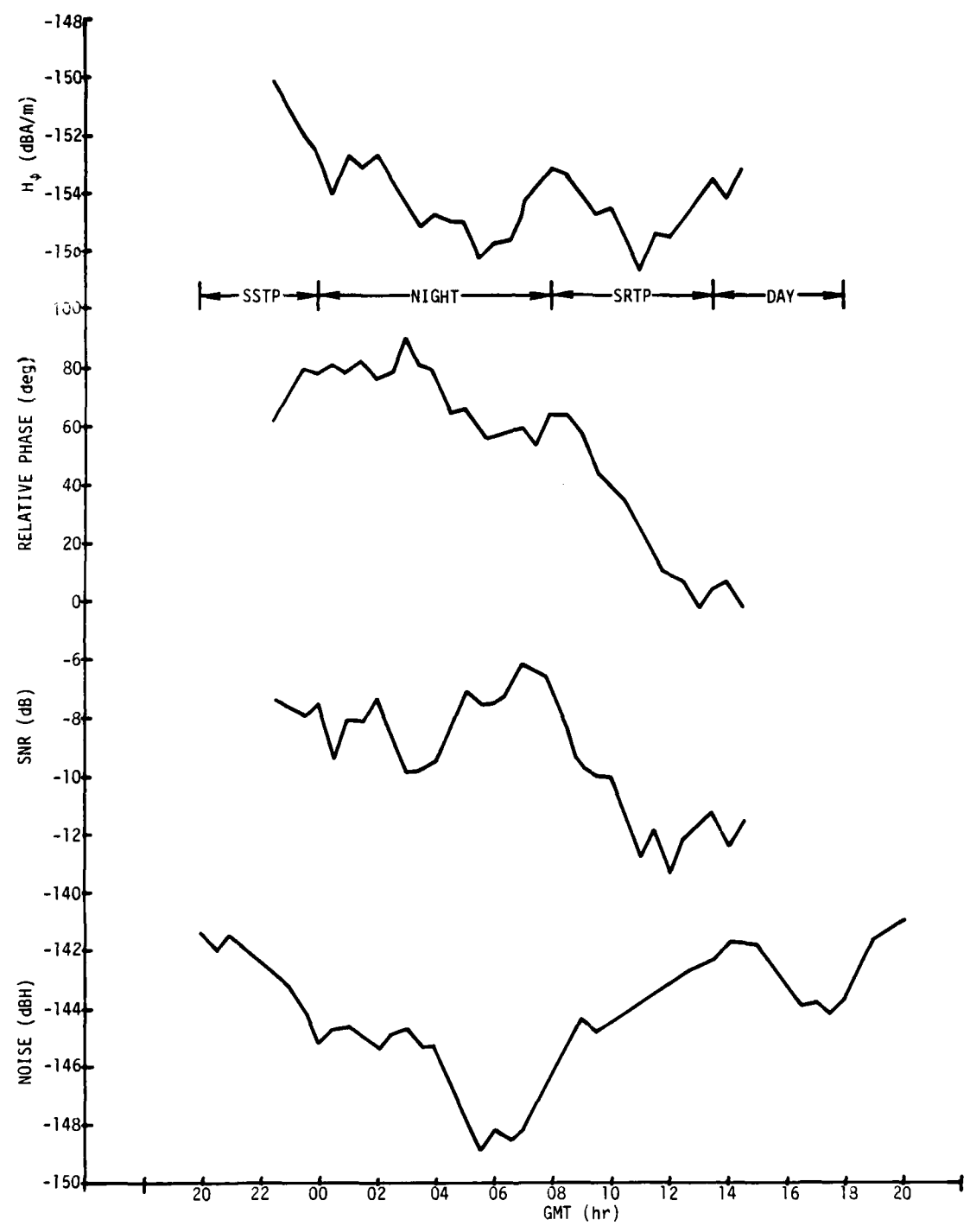


Figure A-1. North-Atlantic-Area Submarine Data Versus GMT, 30 and 31 December 1977

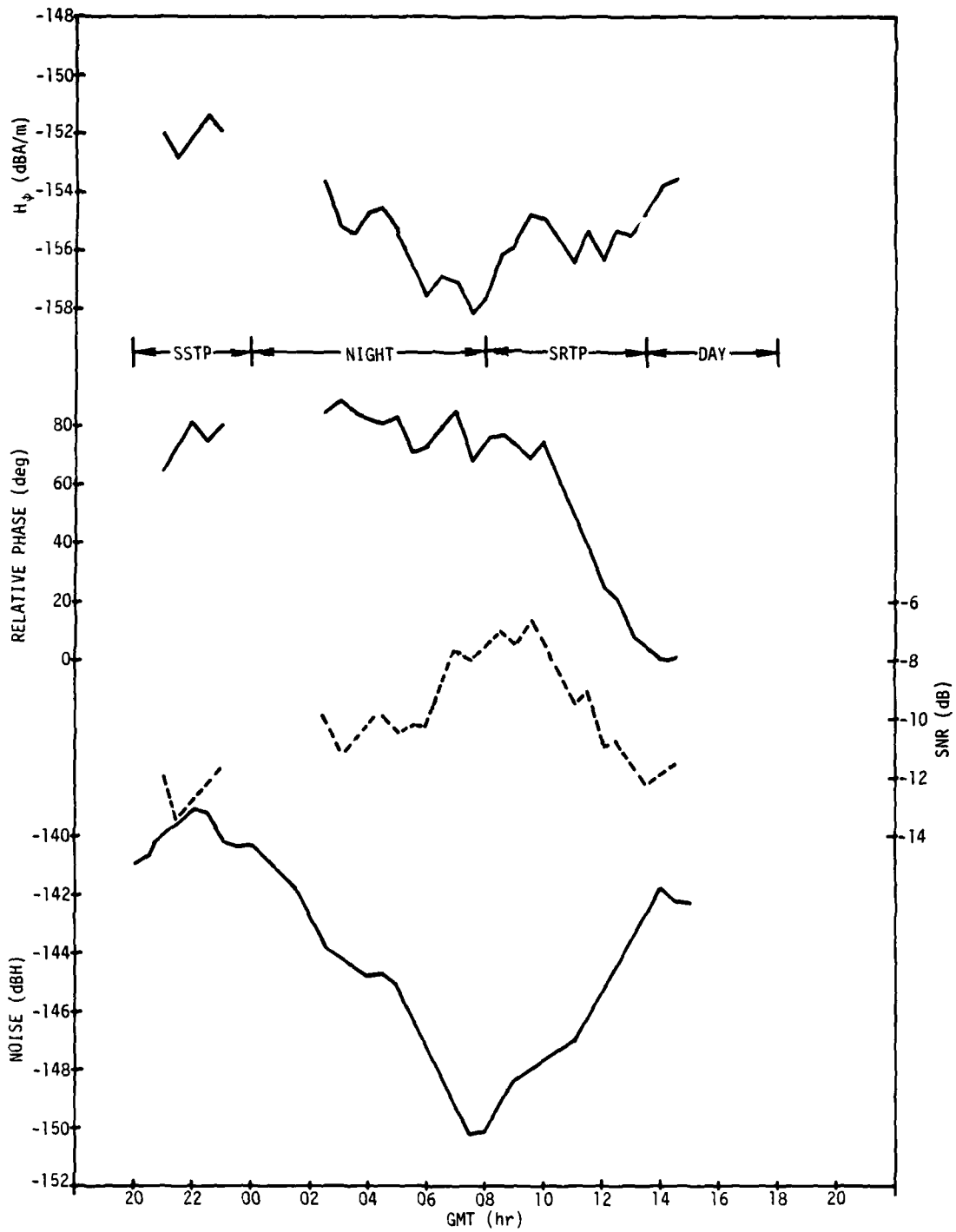


Figure A-2. North-Atlantic-Area Submarine Data Versus GMT, 31 December 1977 and 1 January 1978

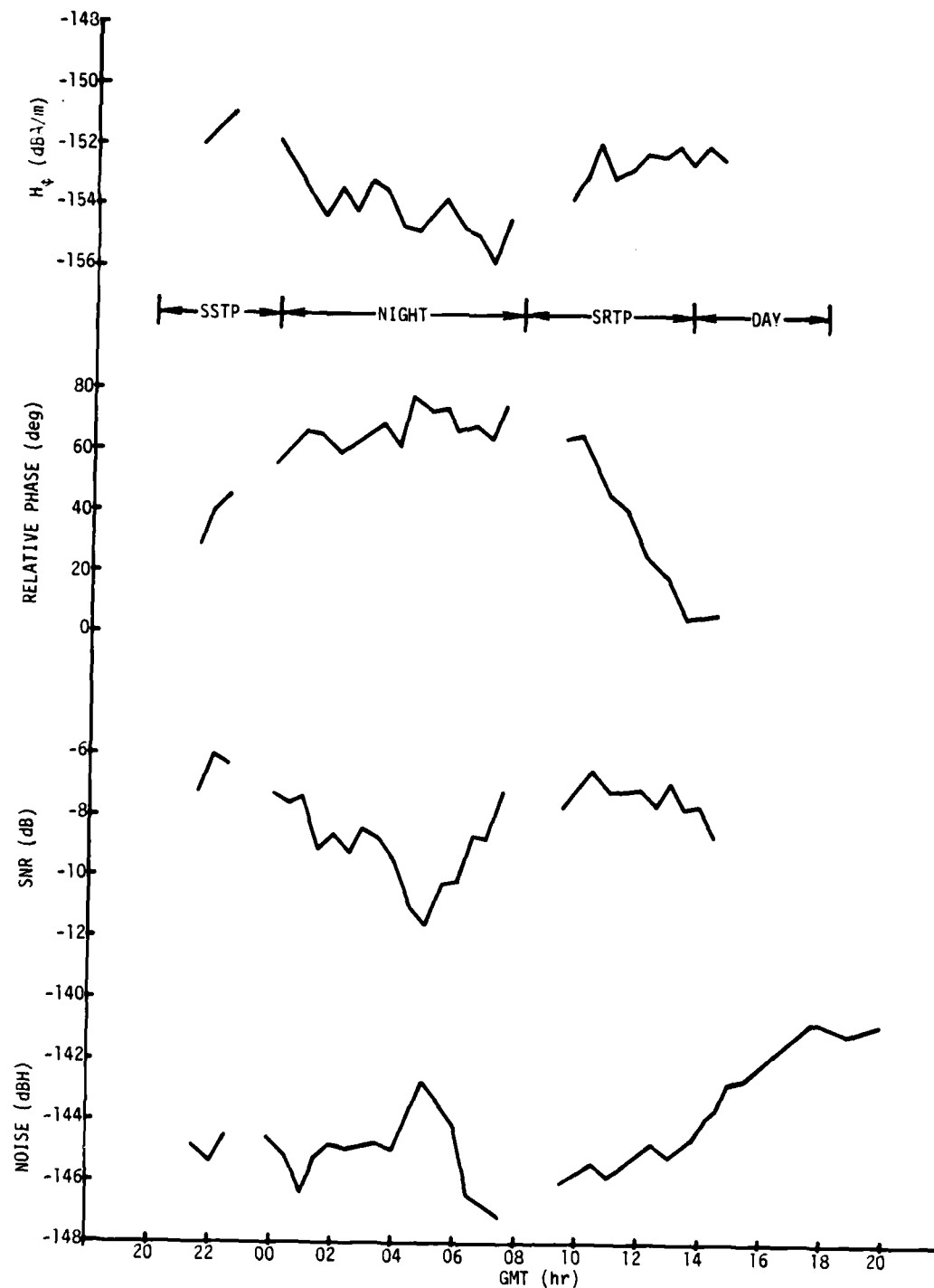


Figure A-3. North-Atlantic-Area Submarine Data Versus GMT, 20 and 21 January 1978

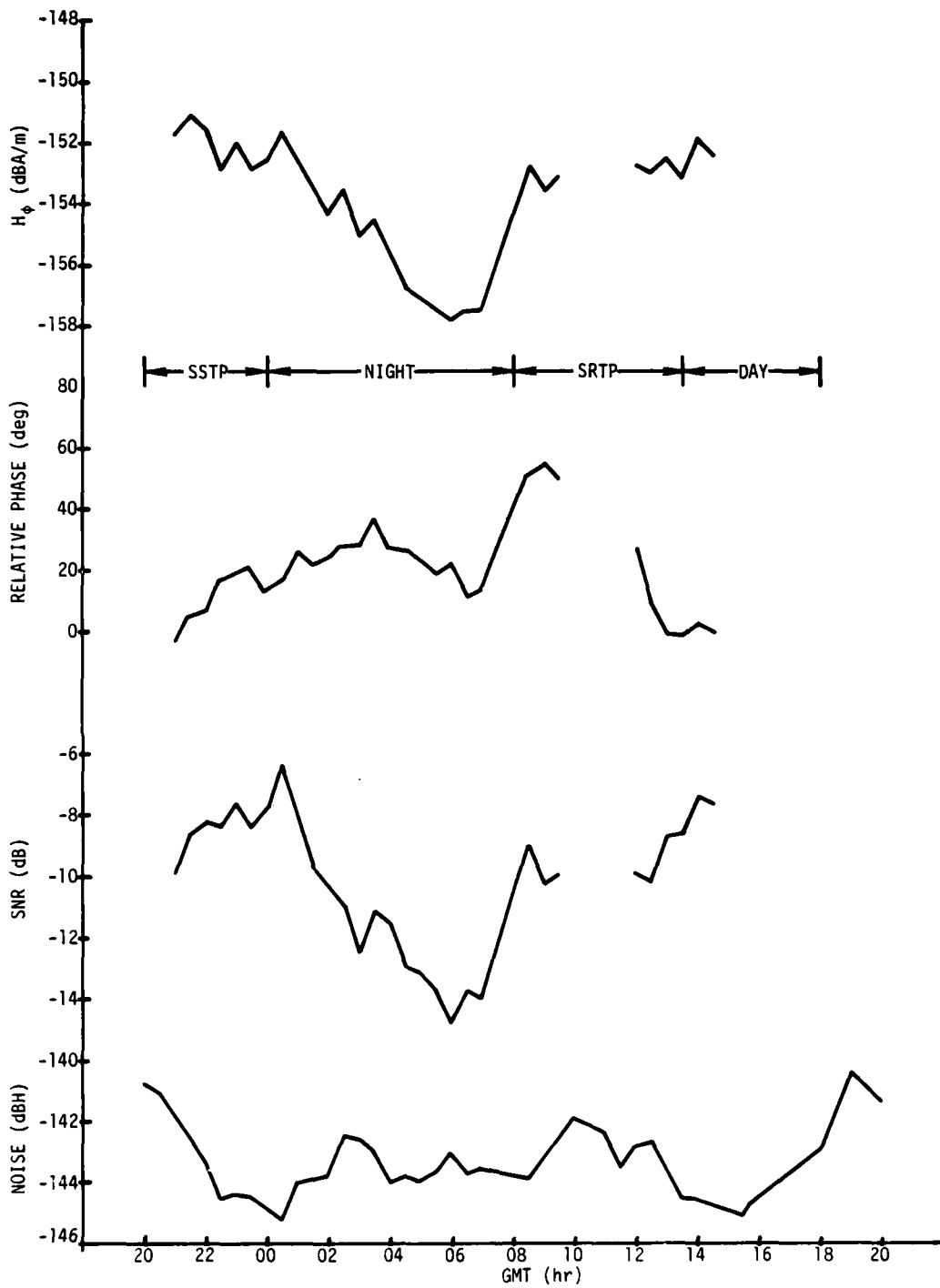


Figure A-4. North-Atlantic-Area Submarine Data Versus GMT, 21 and 22 January 1978



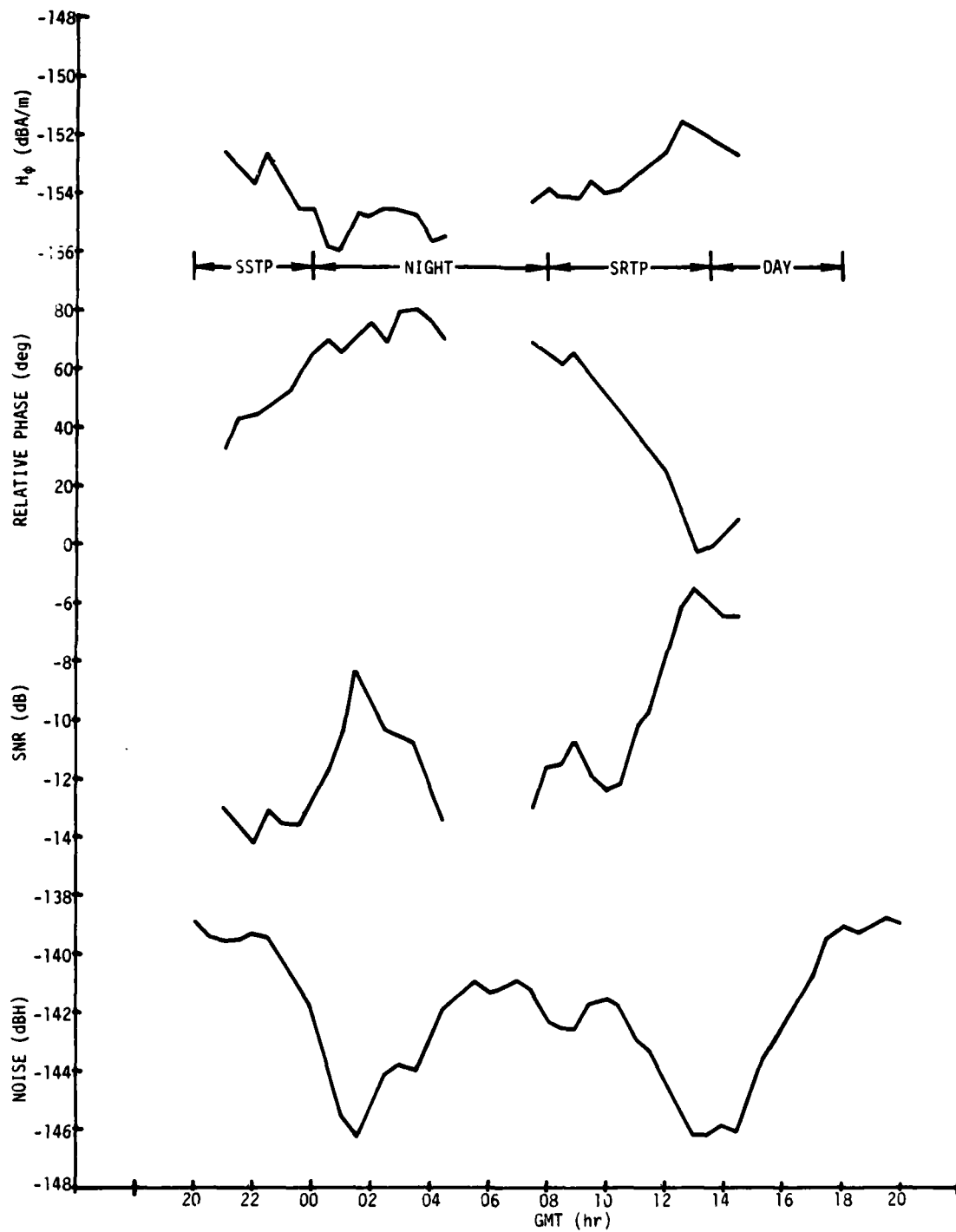


Figure A-5. North-Atlantic-Area Submarine Data Versus GMT, 23 and 24 January 1978

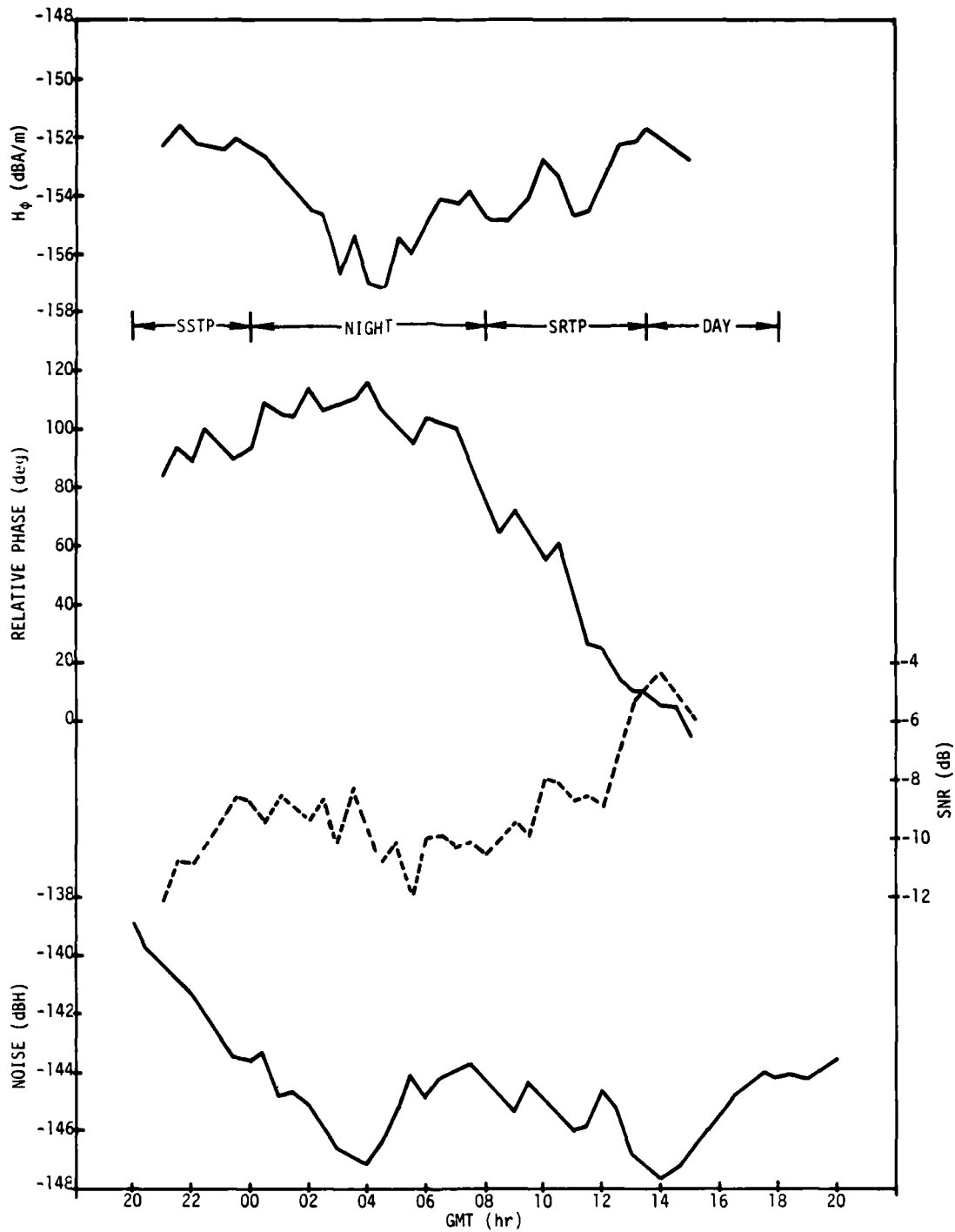


Figure A-6. North-Atlantic-Area Submarine Data Versus GMT, 24 and 25 January 1978

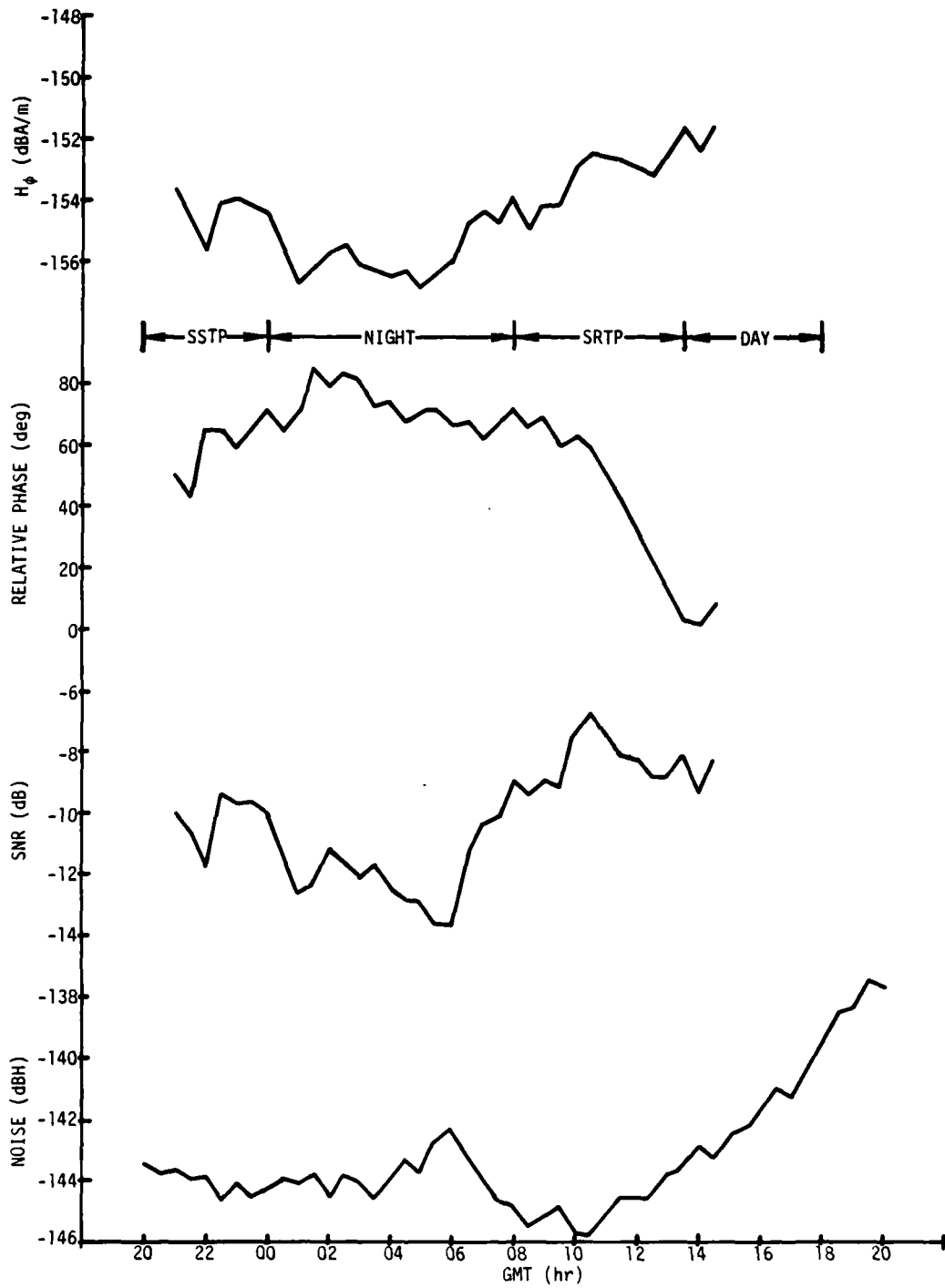


Figure A-7. North-Atlantic-Area Submarine Data Versus GMT, 25 and 26 January 1978

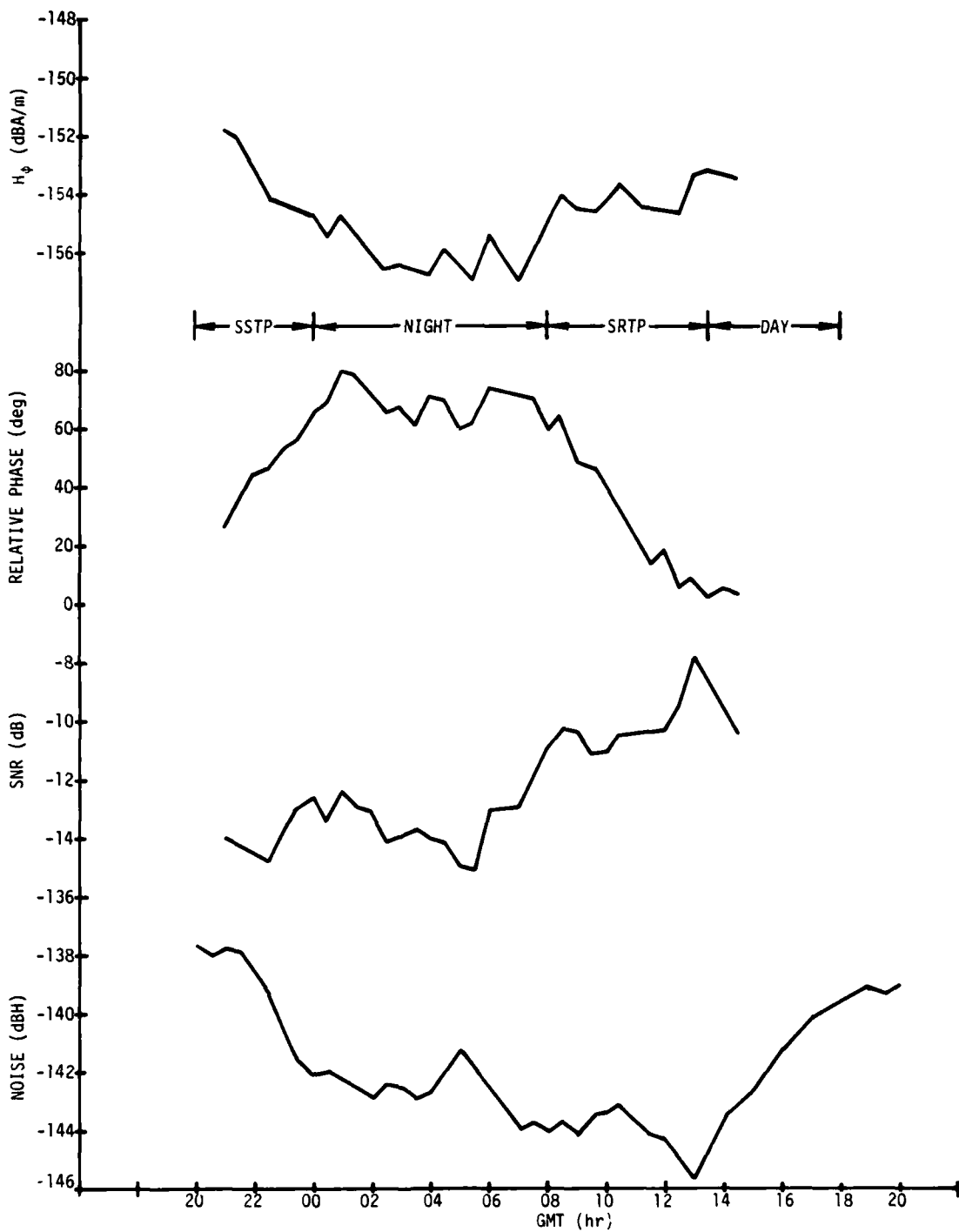


Figure A-8. North-Atlantic-Area Submarine Data Versus GMT, 26 and 27 January 1978

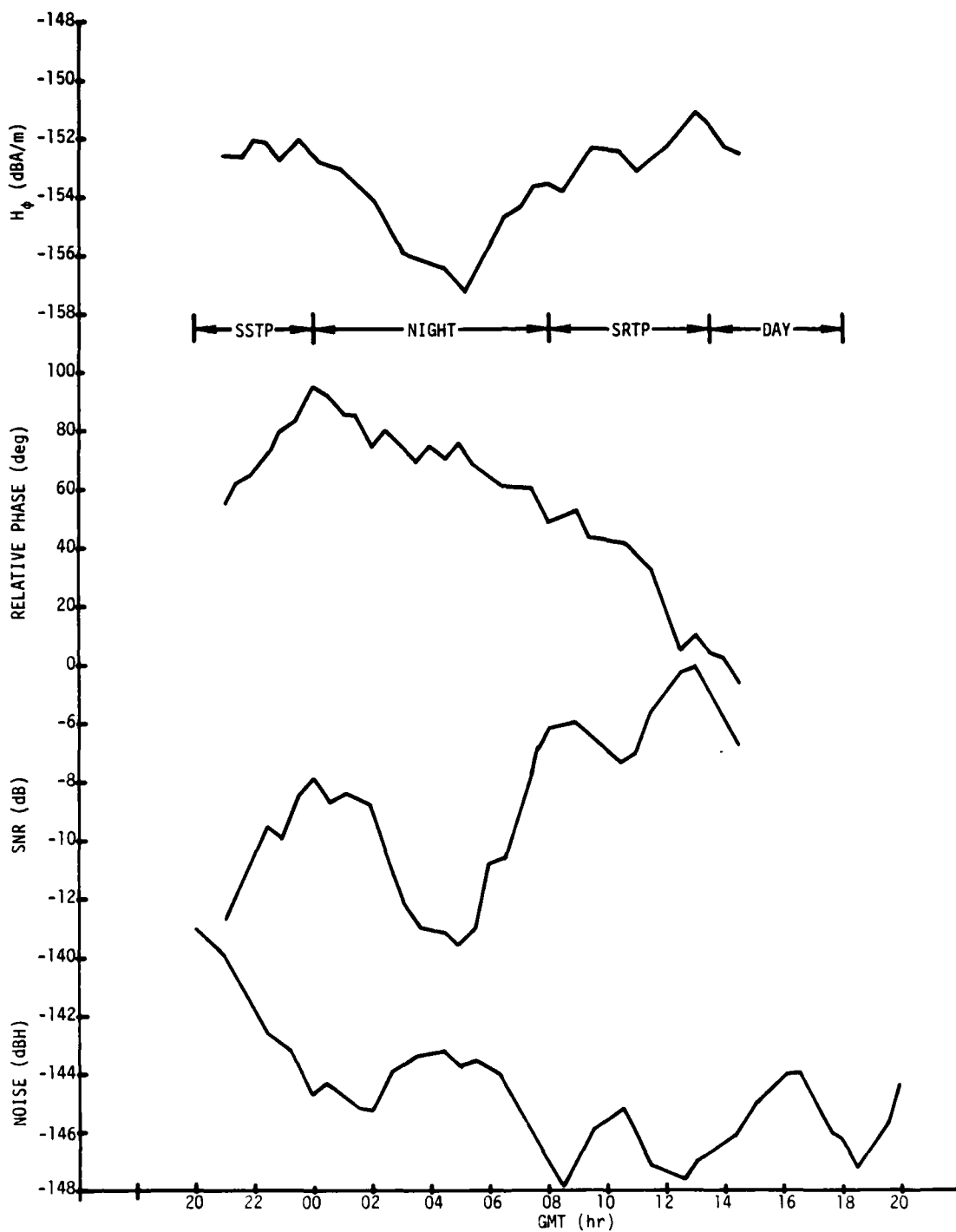


Figure A-9. North-Atlantic-Area Submarine Data Versus GMT, 27 and 28 January 1978

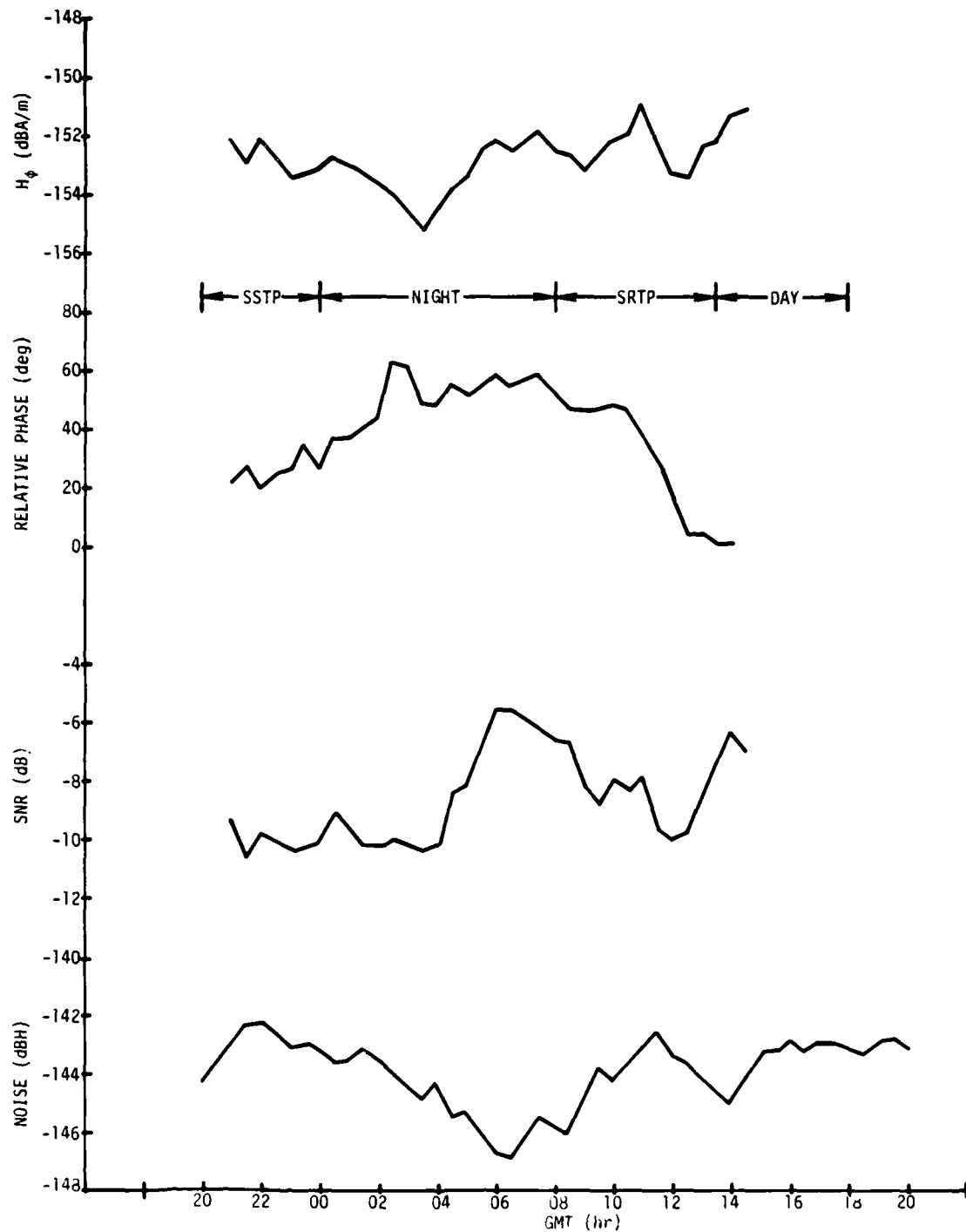


Figure A-10. North-Atlantic-Area Submarine Data Versus GMT, 28 and 29 January 1978

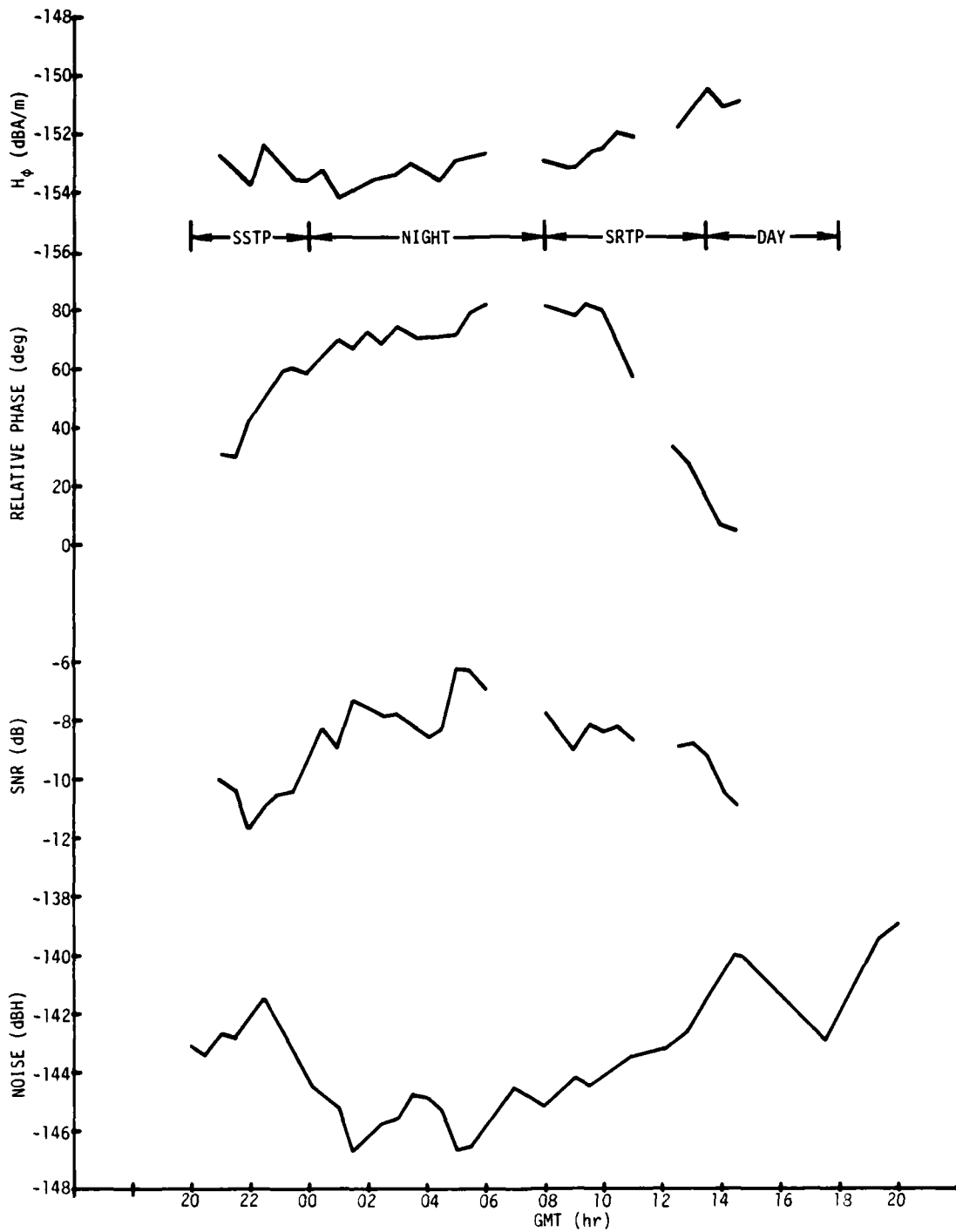


Figure A-11. North-Atlantic-Area Submarine Data Versus GMT, 29 and 30 January 1978

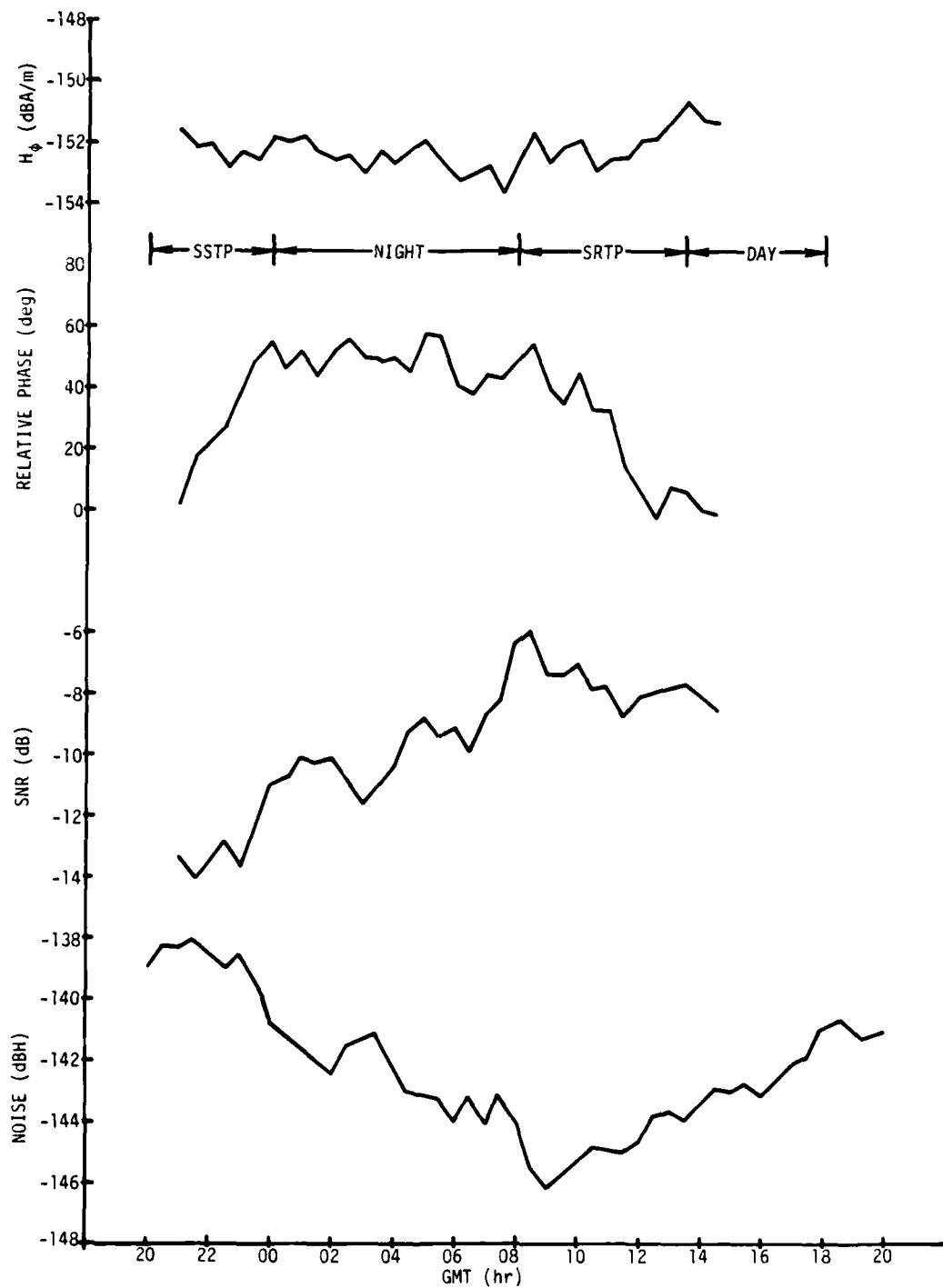


Figure A-12. North-Atlantic-Area Submarine Data Versus GMT, 30 and 31 January 1978



## Appendix B

## FEBRUARY 1978 NORTH-ATLANTIC-AREA SUBMARINE DAILY DATA

During February of 1978, data were obtained on 24 days from the North-Atlantic-area submarine. The daily field-strength (both amplitude and relative phase), effective-noise, and SNR values are plotted versus GMT in figures B-1 through B-24 in this appendix. The WTF antenna phasing angle ( $\psi$ ) was 291 deg and the transmitting frequency was  $76 \pm 4$  Hz.

Amplitude peak-to-trough variations of 6 dB or greater did not occur during the 24 measurement days. The minimum nighttime field strength was usually measured from 0400 to 0800 GMT.

The night-to-day relative phase variation was  $\sim 56$  deg, with the largest variation (88 deg) occurring on 12 and 23 February (figures B-11 and B-22), and the smallest variation (-6 and 7 deg) occurring during the first two days following the 13 February PCA event (figures B-13 and B-14).

The largest daily peak-to-trough variations in the effective noise (8 to 9 dB) occurred during 1, 3, 19, 21, and 25 February (figures B-1, B-3, B-18, B-20, and B-24).

It should be noted that all of the submarine effective-noise data presented in this report are contaminated to some degree by submarine-generated noise (external or internal to the submarine). Thus, the effective-noise values presented here are on the high side.

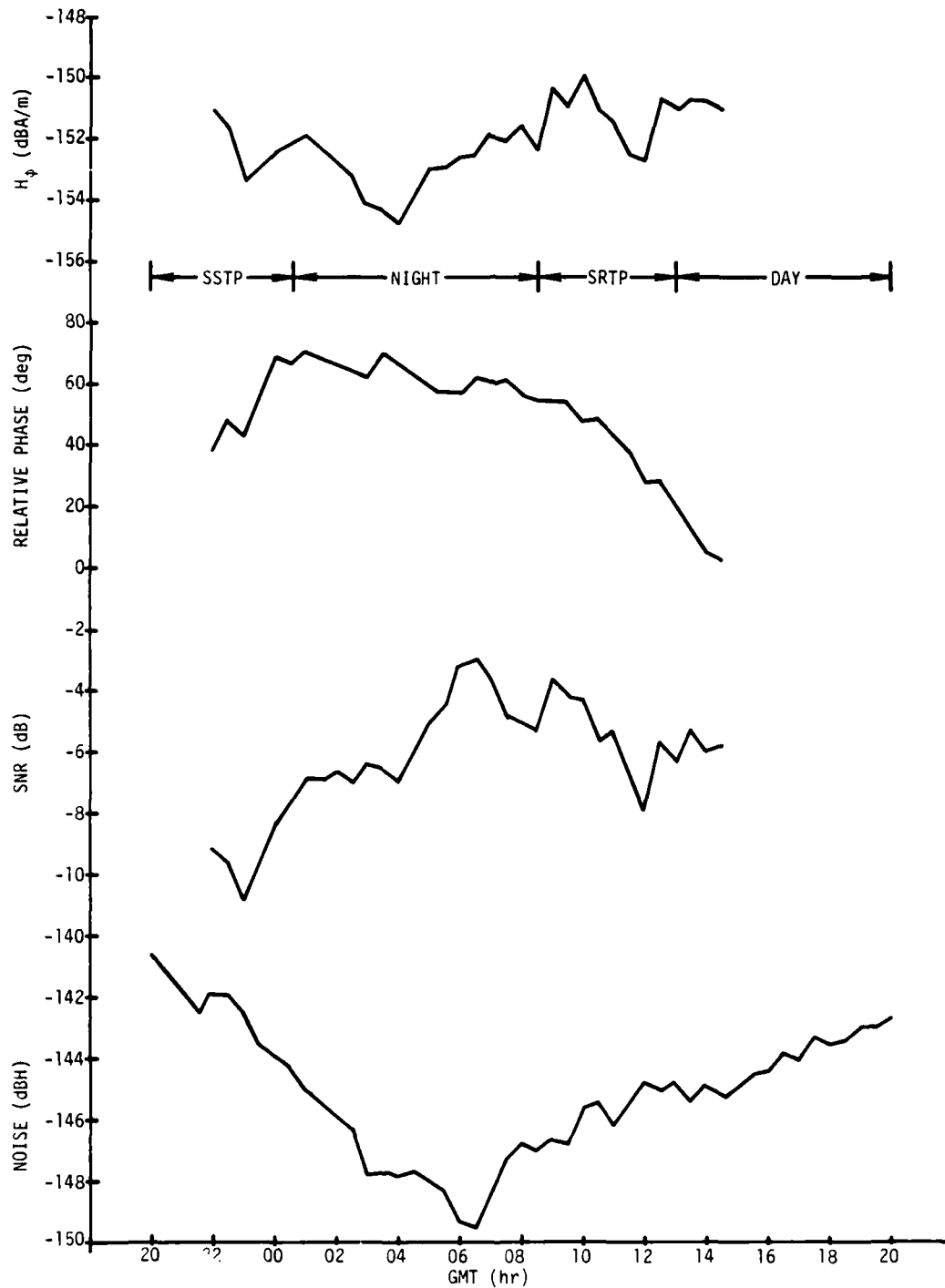


Figure B-1. North-Atlantic-Area Submarine Data Versus GMT, 31 January and 1 February 1978

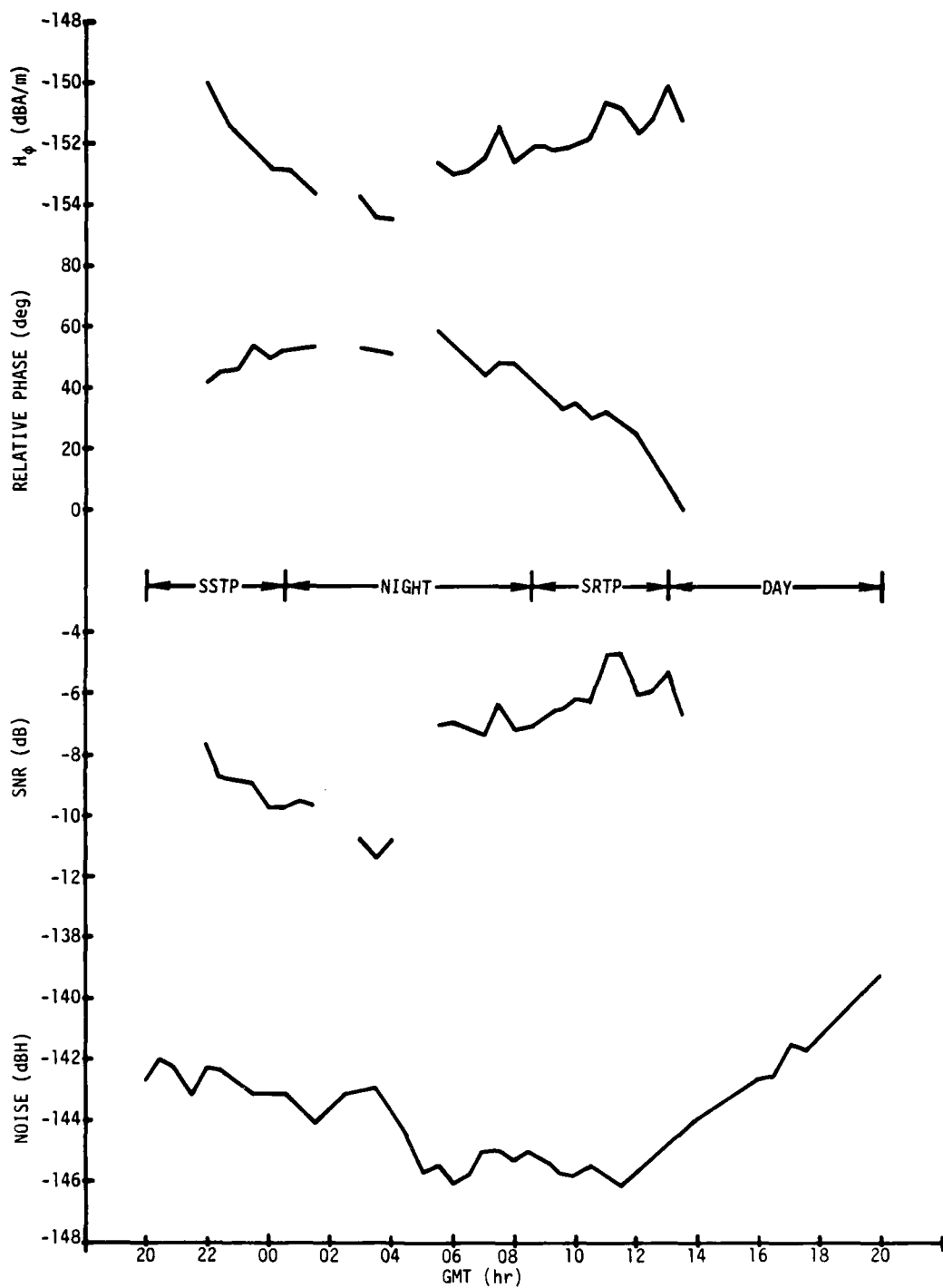


Figure B-2. North-Atlantic-Area Submarine Data Versus GMT, 1 and 2 February 1978

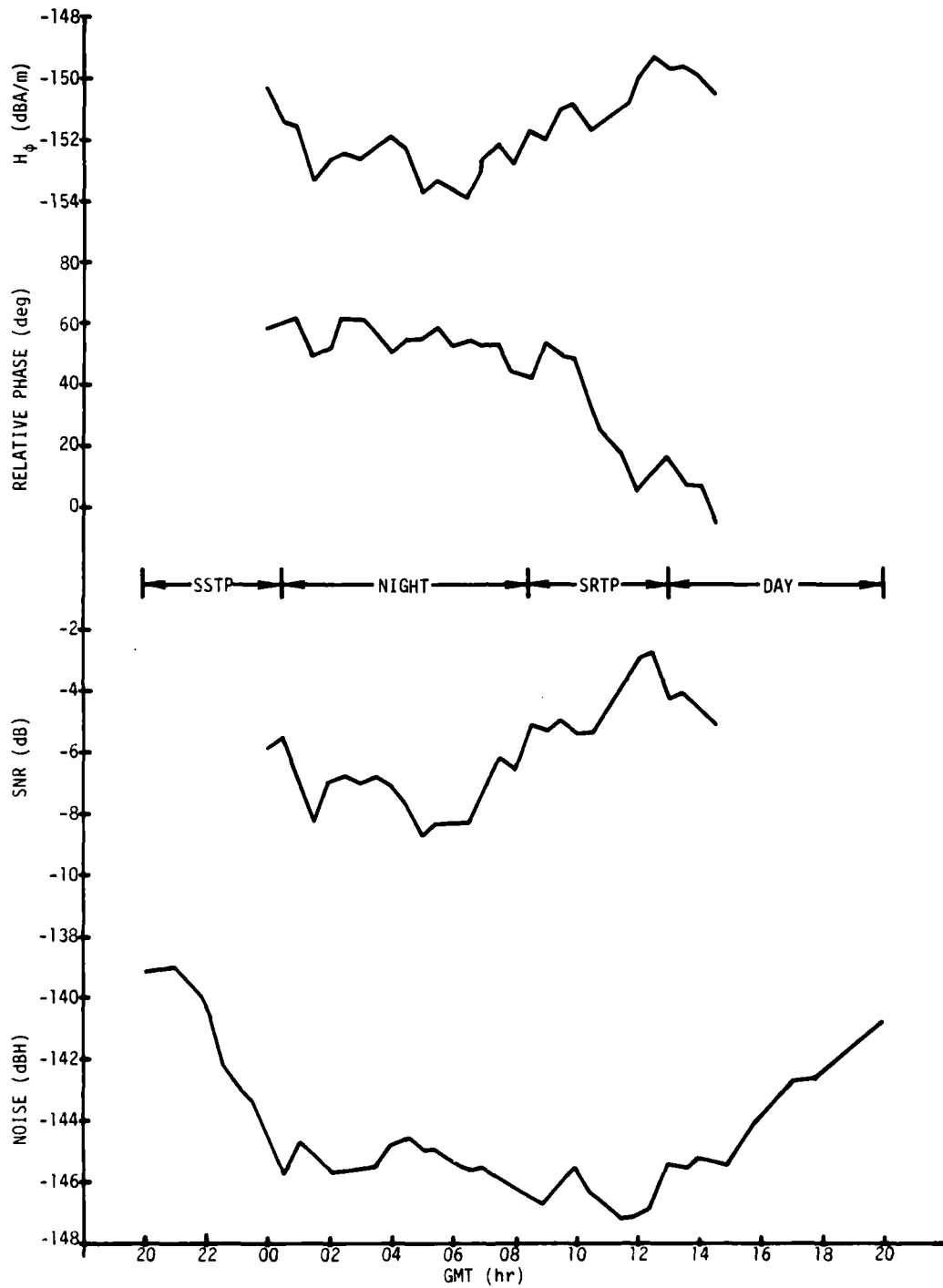


Figure B-3. North-Atlantic-Area Submarine Data Versus GMT, 2 and 3 February 1978

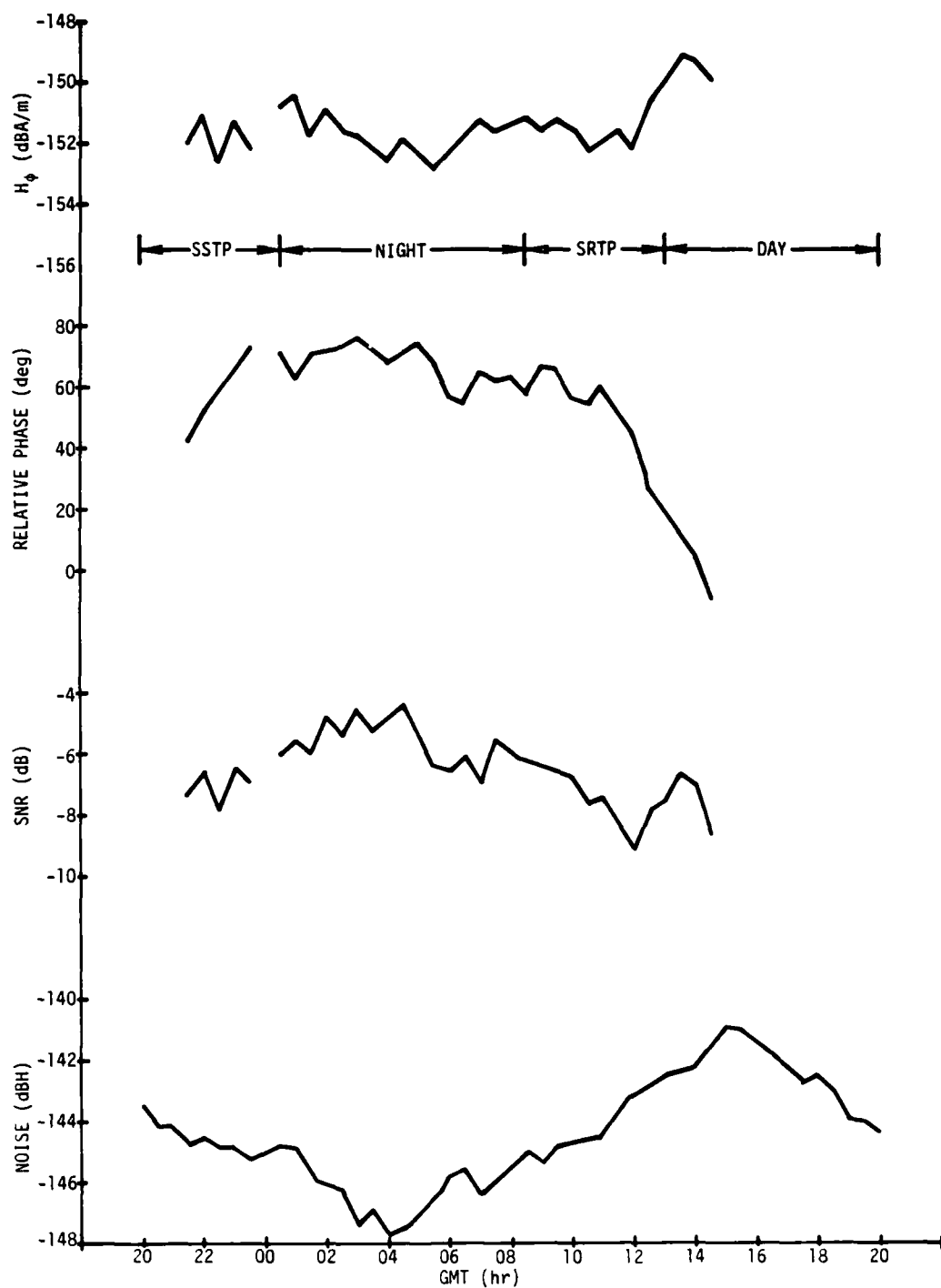


Figure B-4. North-Atlantic-Area Submarine Data Versus GMT, 4 and 5 February 1978

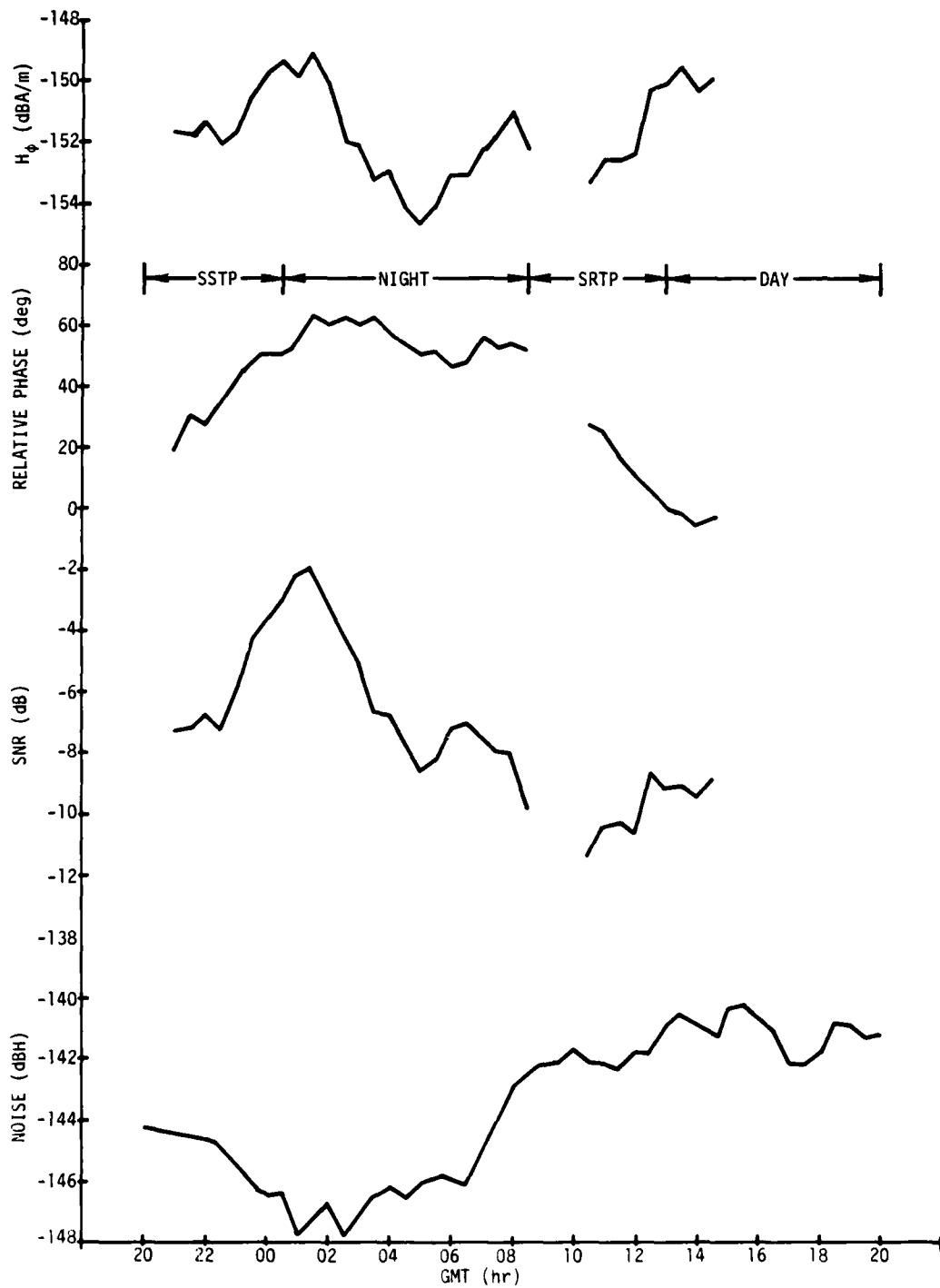


Figure B-5. North-Atlantic-Area Submarine Data Versus GMT, 5 and 6 February 1978

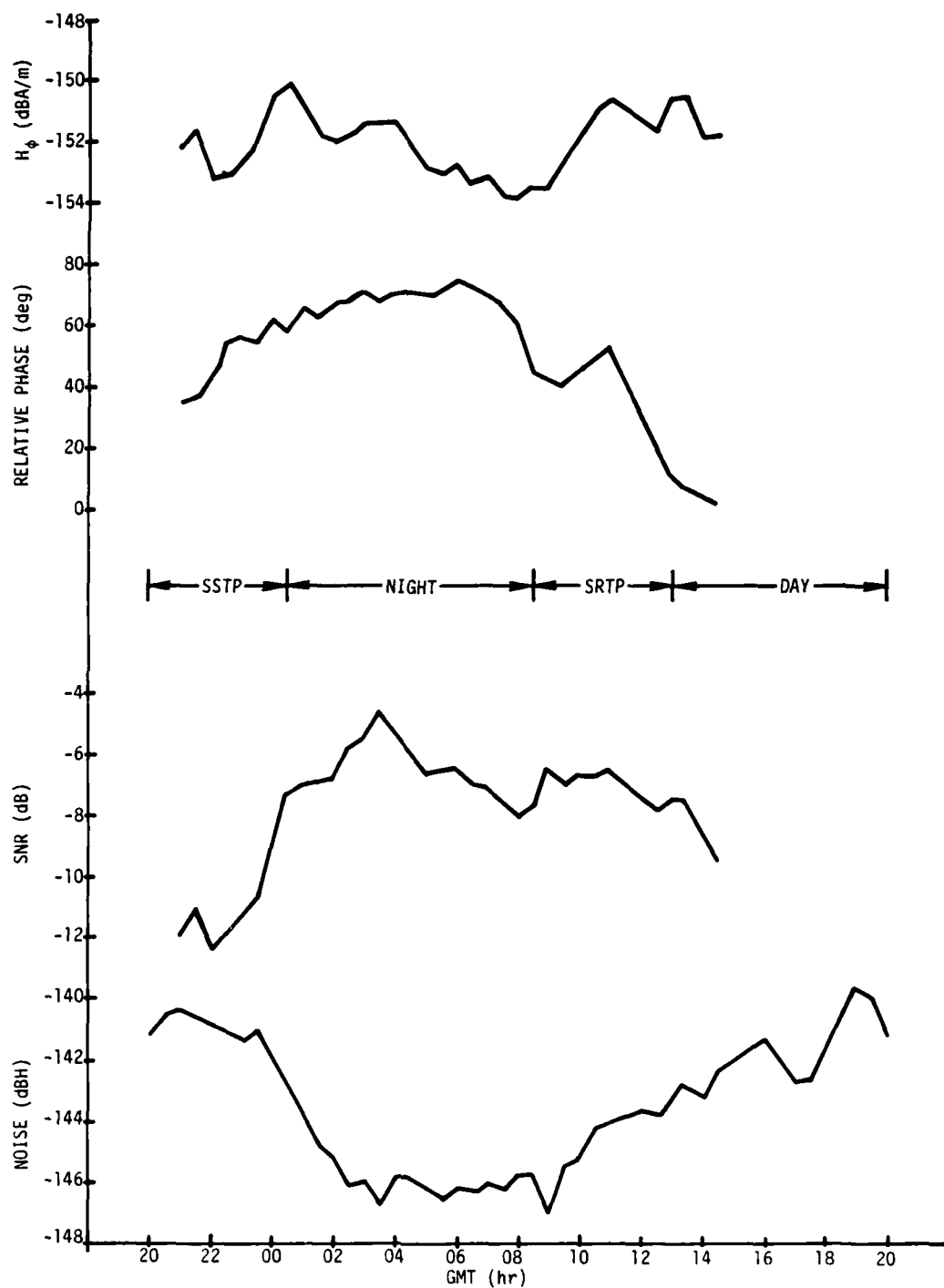


Figure B-6. North-Atlantic-Area Submarine Data Versus GMT, 6 and 7 February 1978

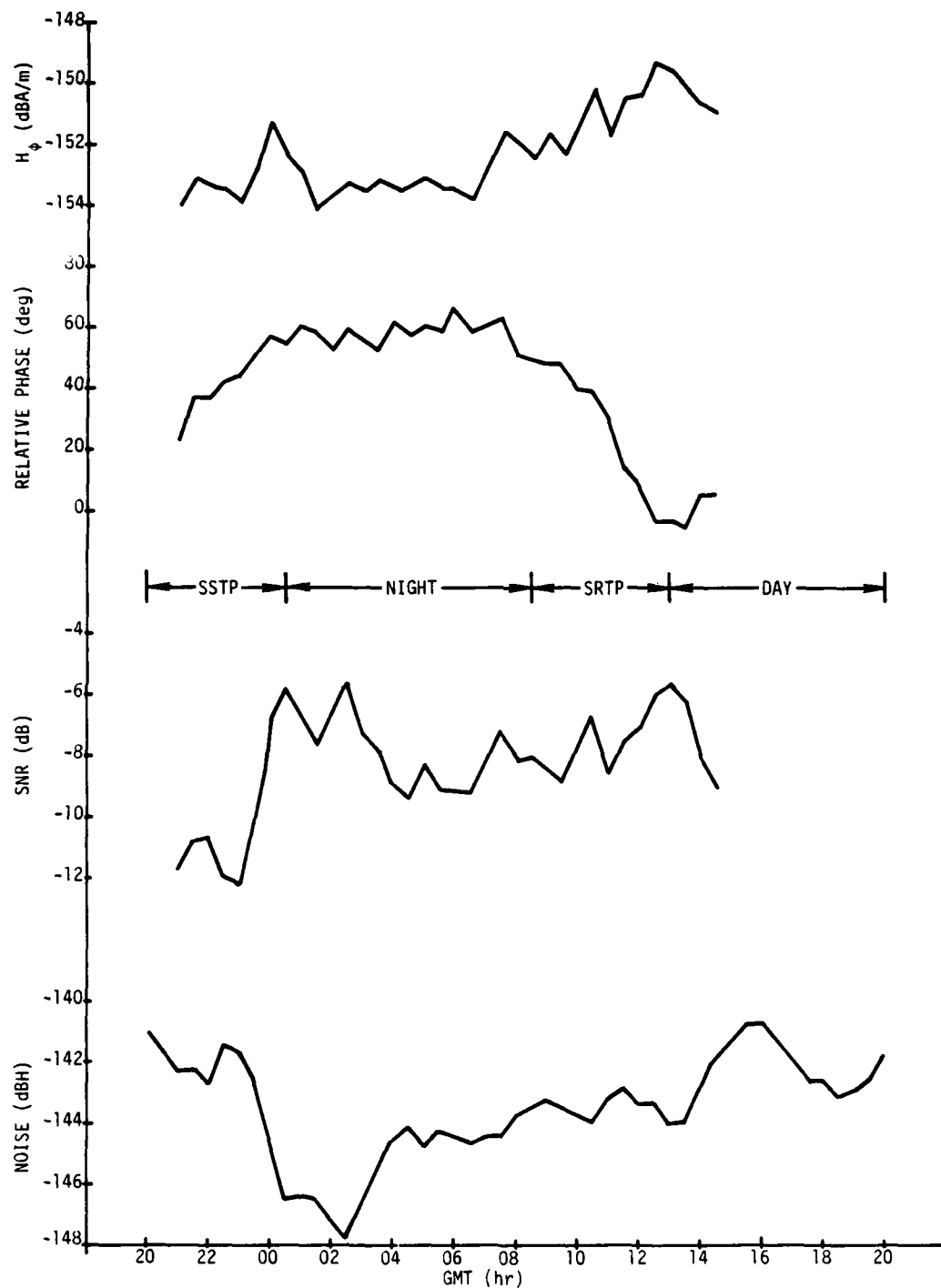


Figure B-7. North-Atlantic-Area Submarine Data Versus GMT, 7 and 8 February 1978



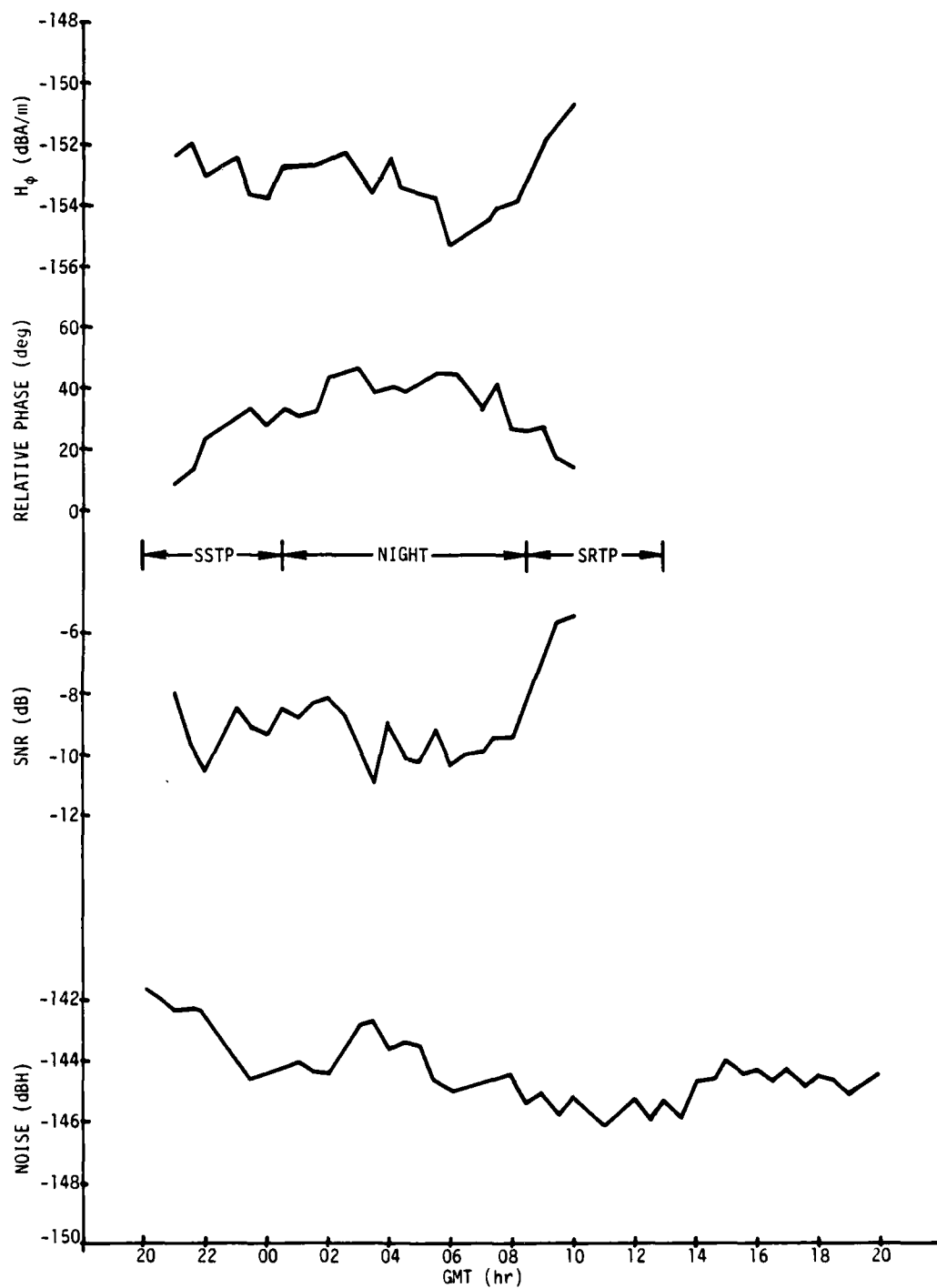


Figure B-8. North-Atlantic-Area Submarine Data Versus GMT, 8 and 9 February 1978

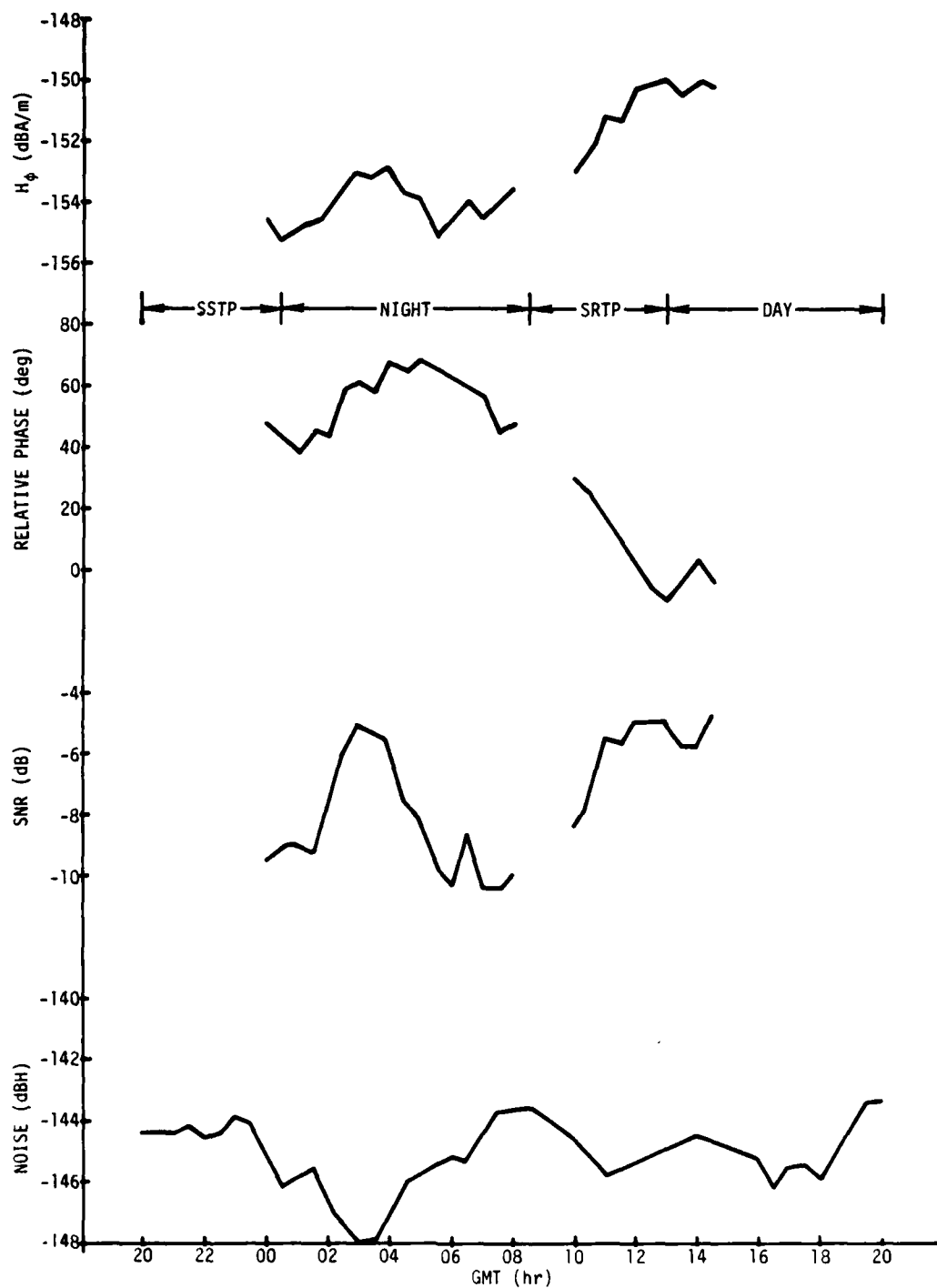


Figure B-9. North-Atlantic-Area Submarine Data Versus GMT, 9 and 10 February 1978

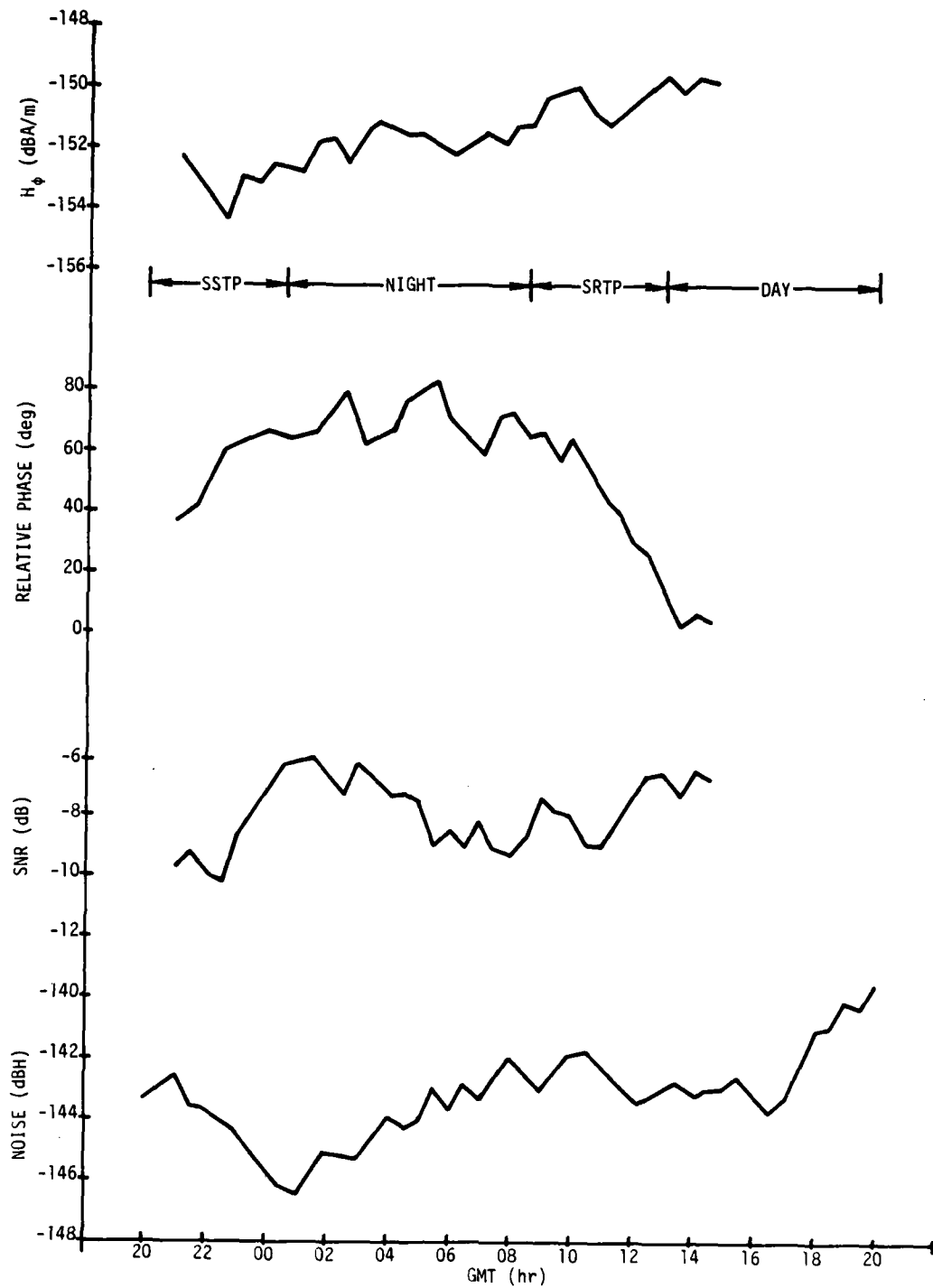


Figure B-10. North-Atlantic-Area Submarine Data Versus GMT, 10 and 11 February 1978

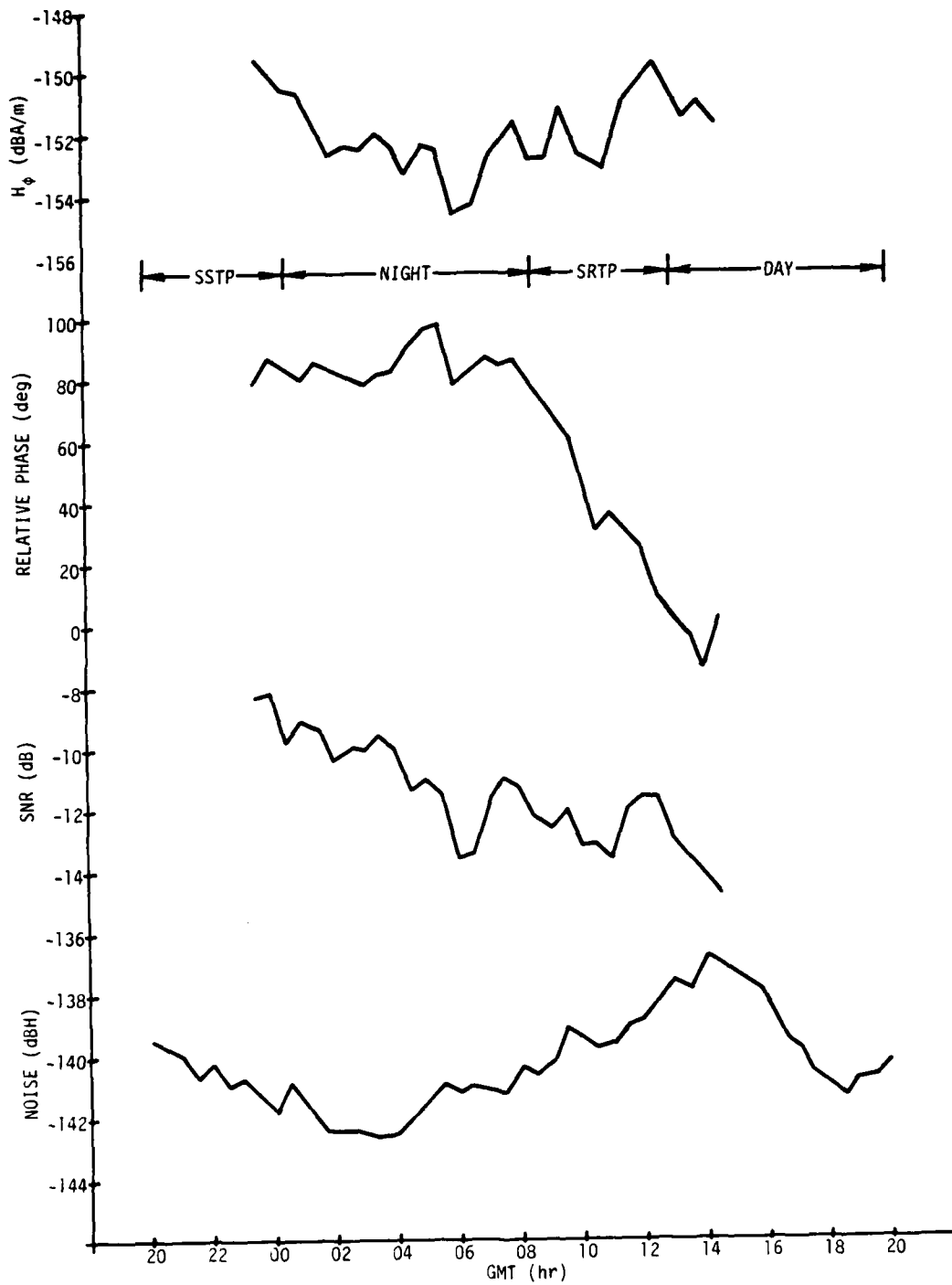


Figure B-11. North-Atlantic-Area Submarine Data Versus GMT, 11 and 12 February 1978

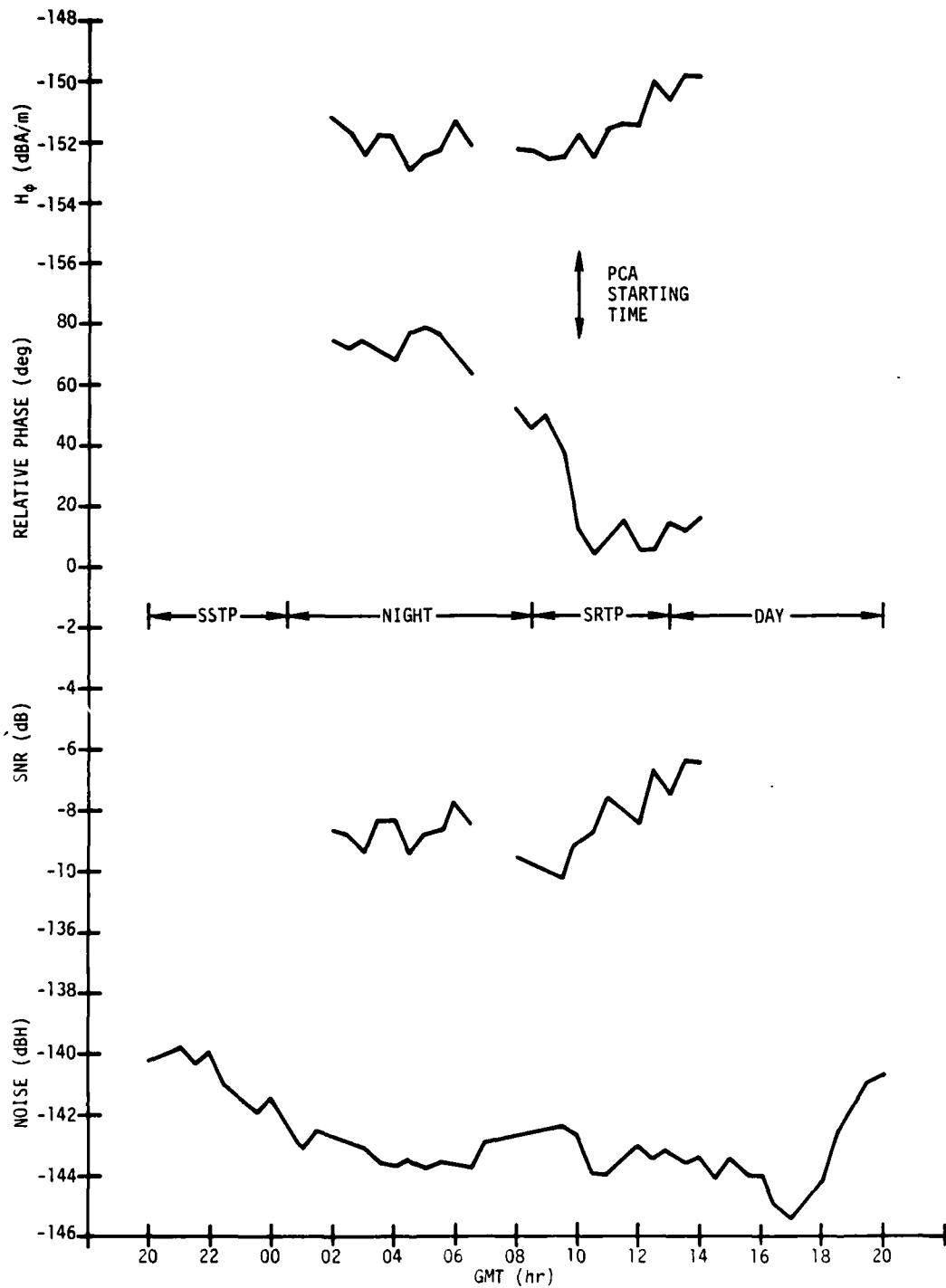


Figure B-12. North-Atlantic-Area Submarine Data Versus GMT, 12 and 13 February 1978

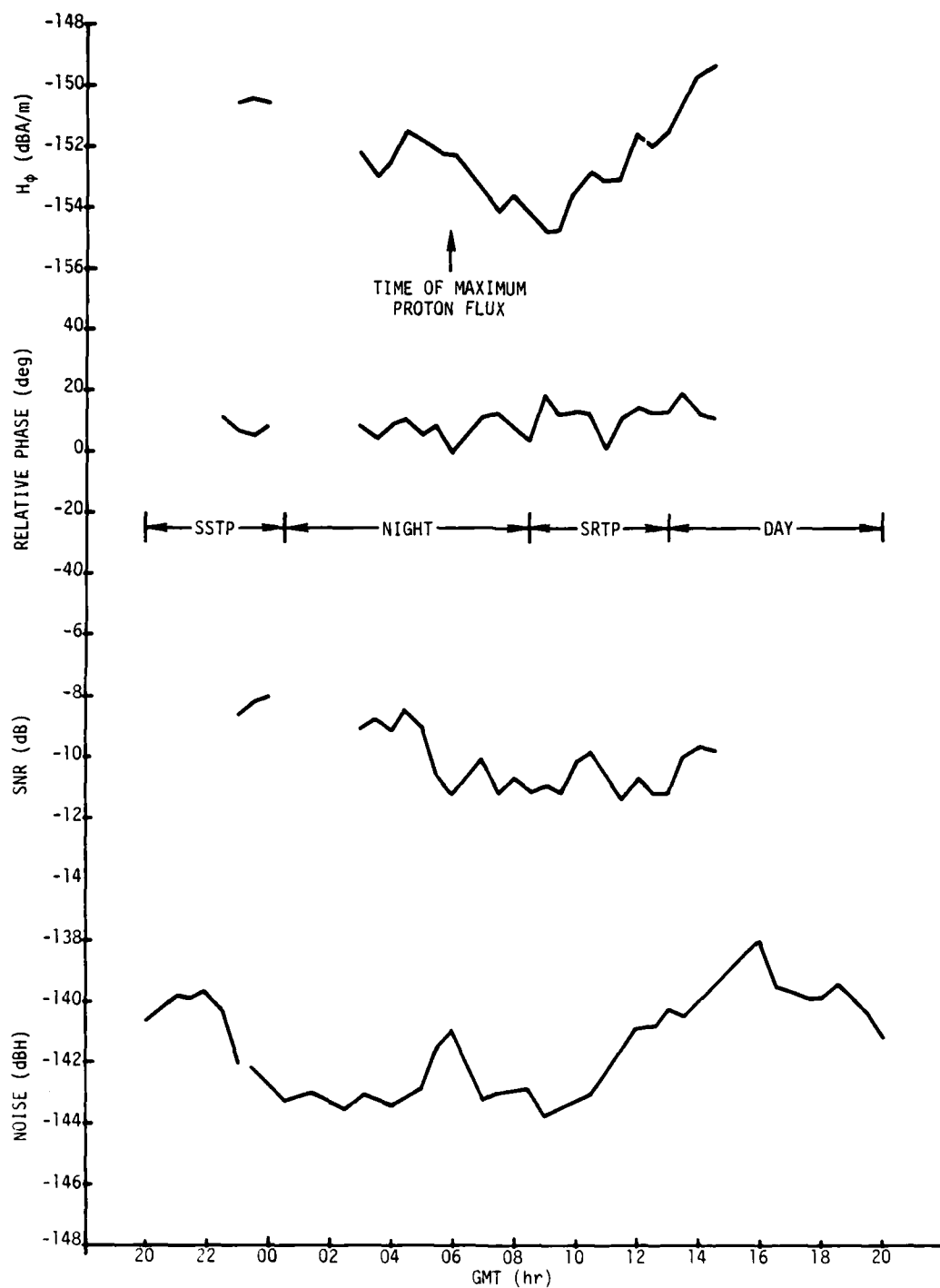


Figure B-13. North-Atlantic-Area Submarine Data Versus GMT, 13 and 14 February 1978

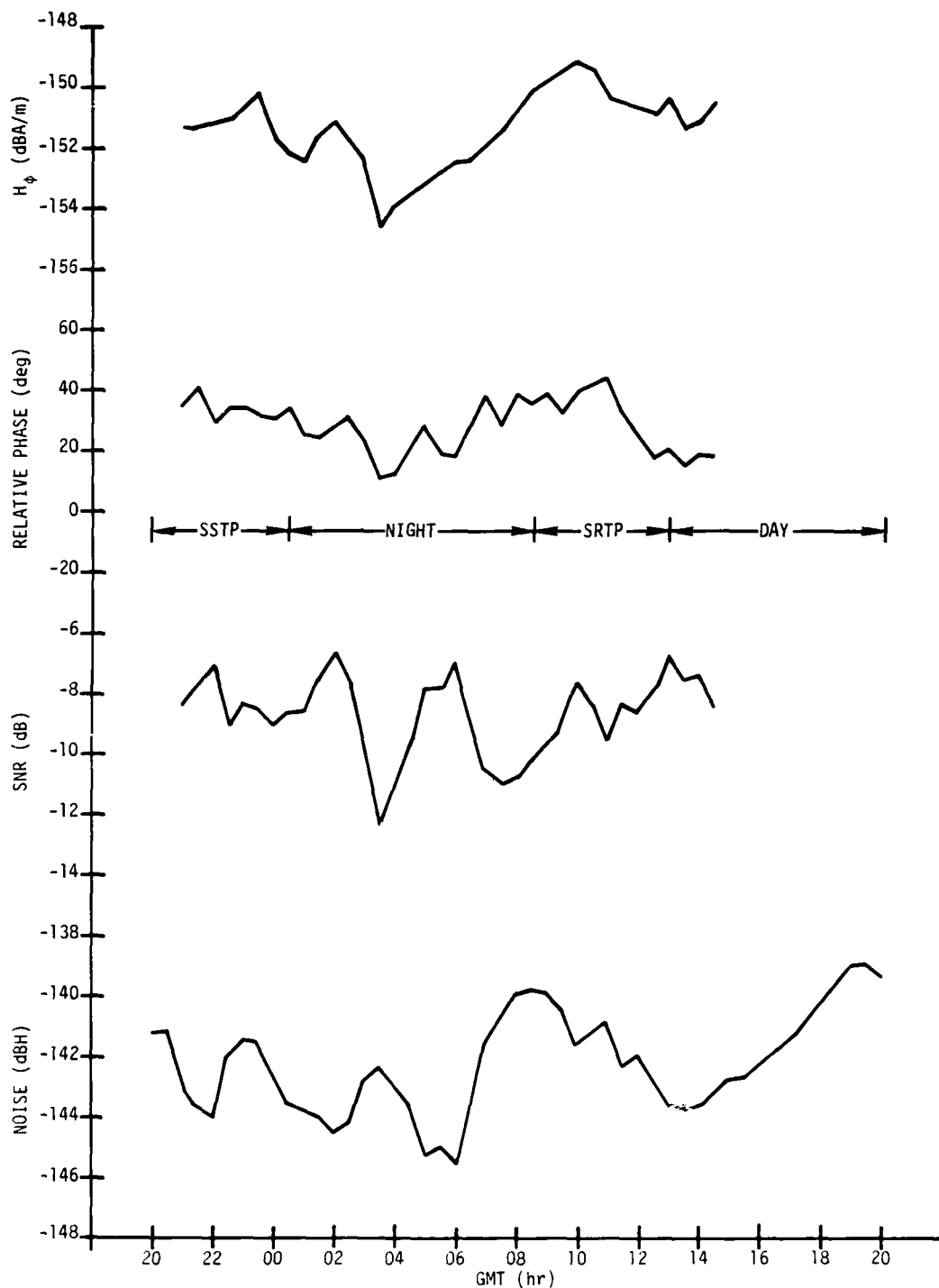


Figure B-14. North-Atlantic-Area Submarine Data Versus GMT, 14 and 15 February 1978

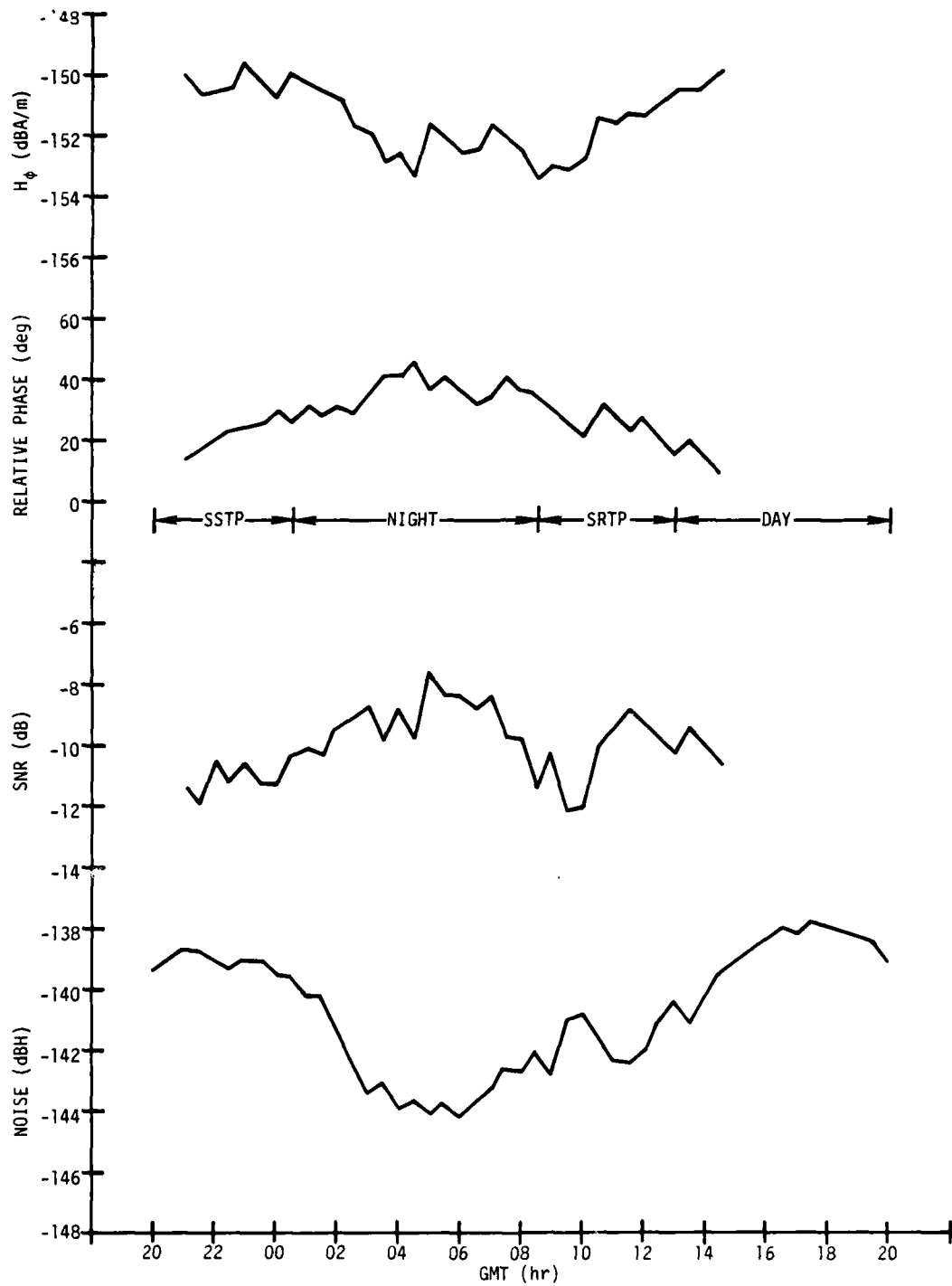


Figure B-15. North-Atlantic-Area Submarine Data Versus GMT, 15 and 16 February 1978



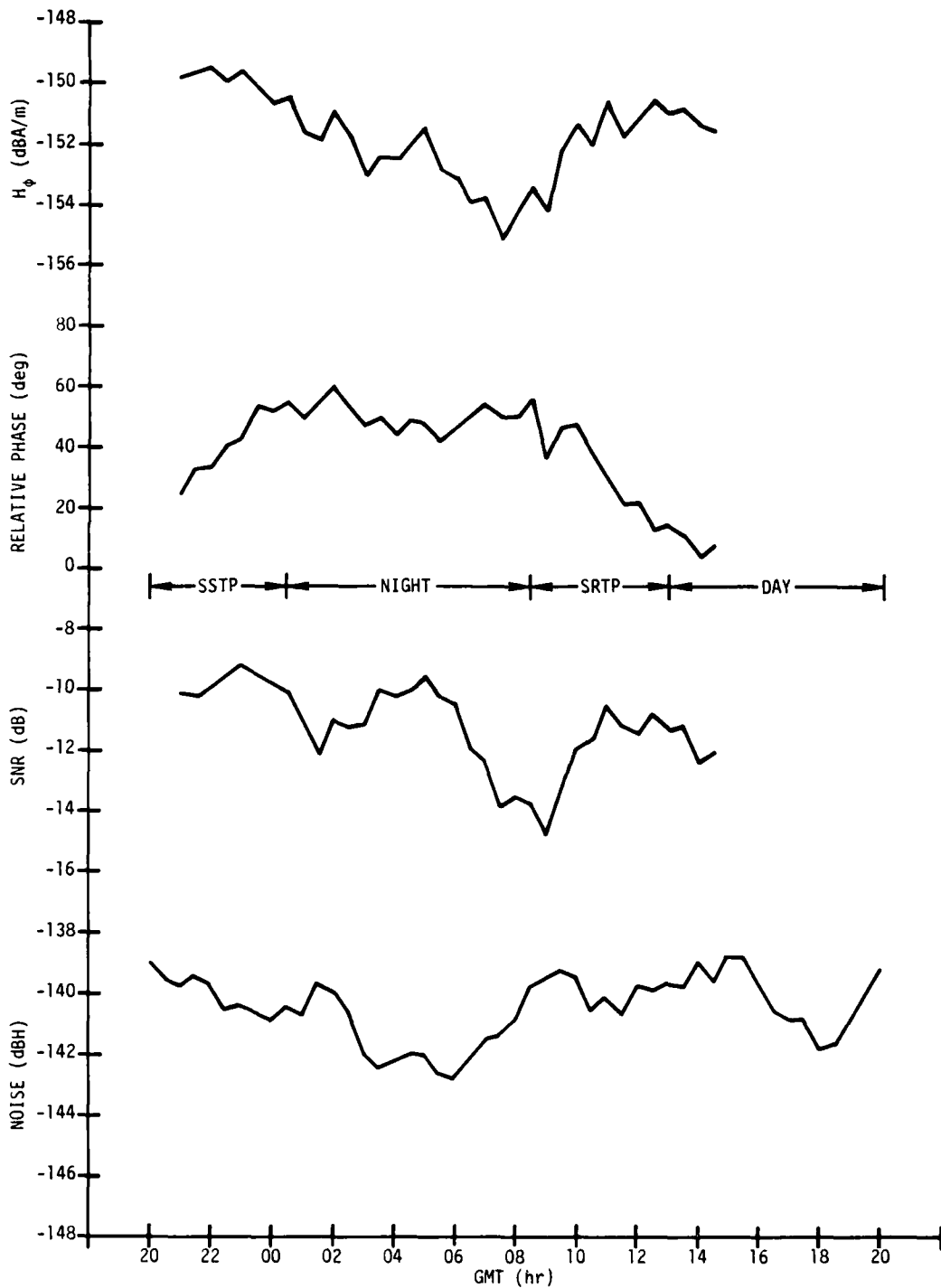


Figure B-16. North-Atlantic-Area Submarine Data Versus GMT, 16 and 17 February 1978

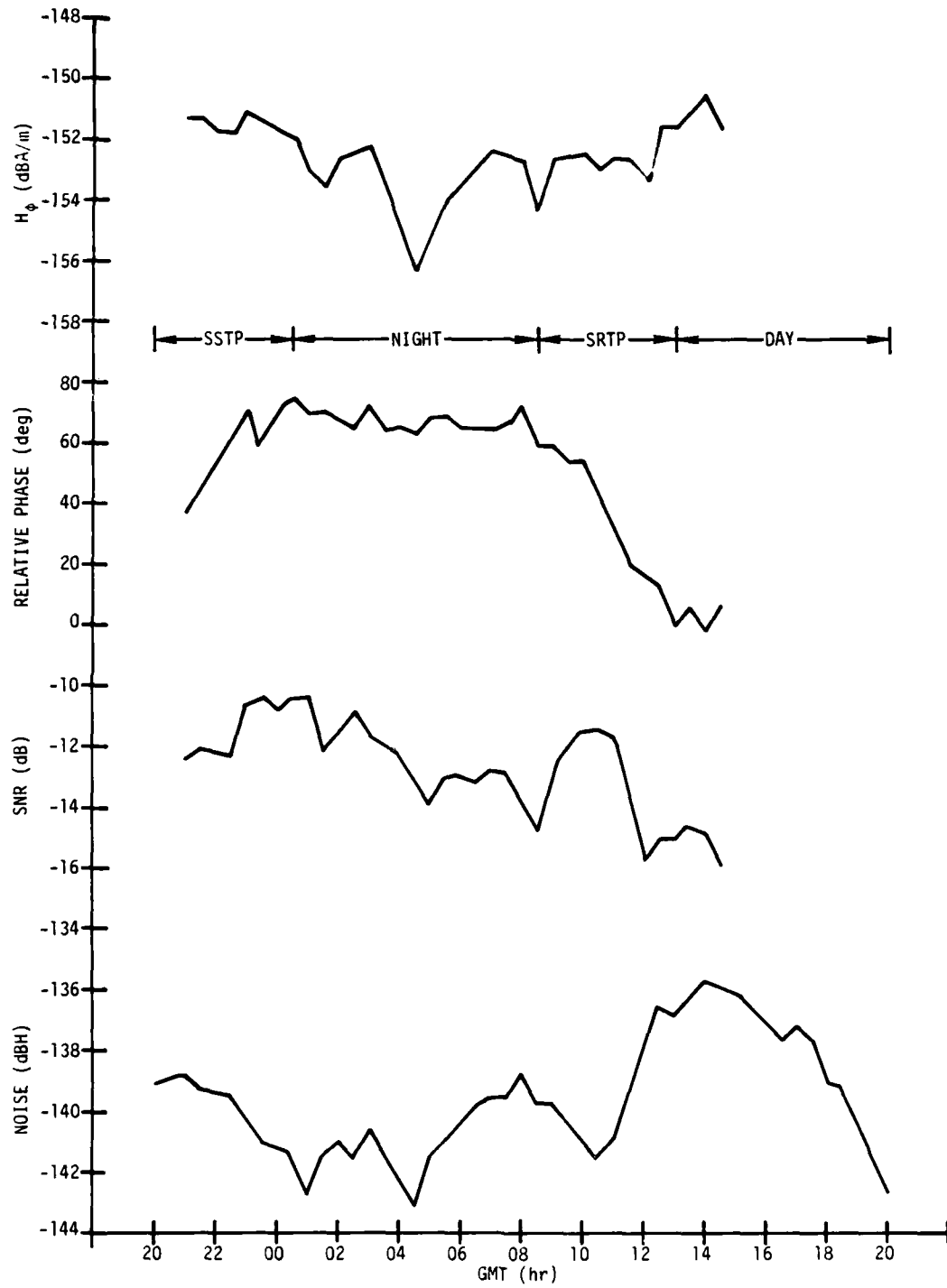


Figure B-17. North-Atlantic-Area Submarine Data Versus GMT, 17 and 18 February 1978

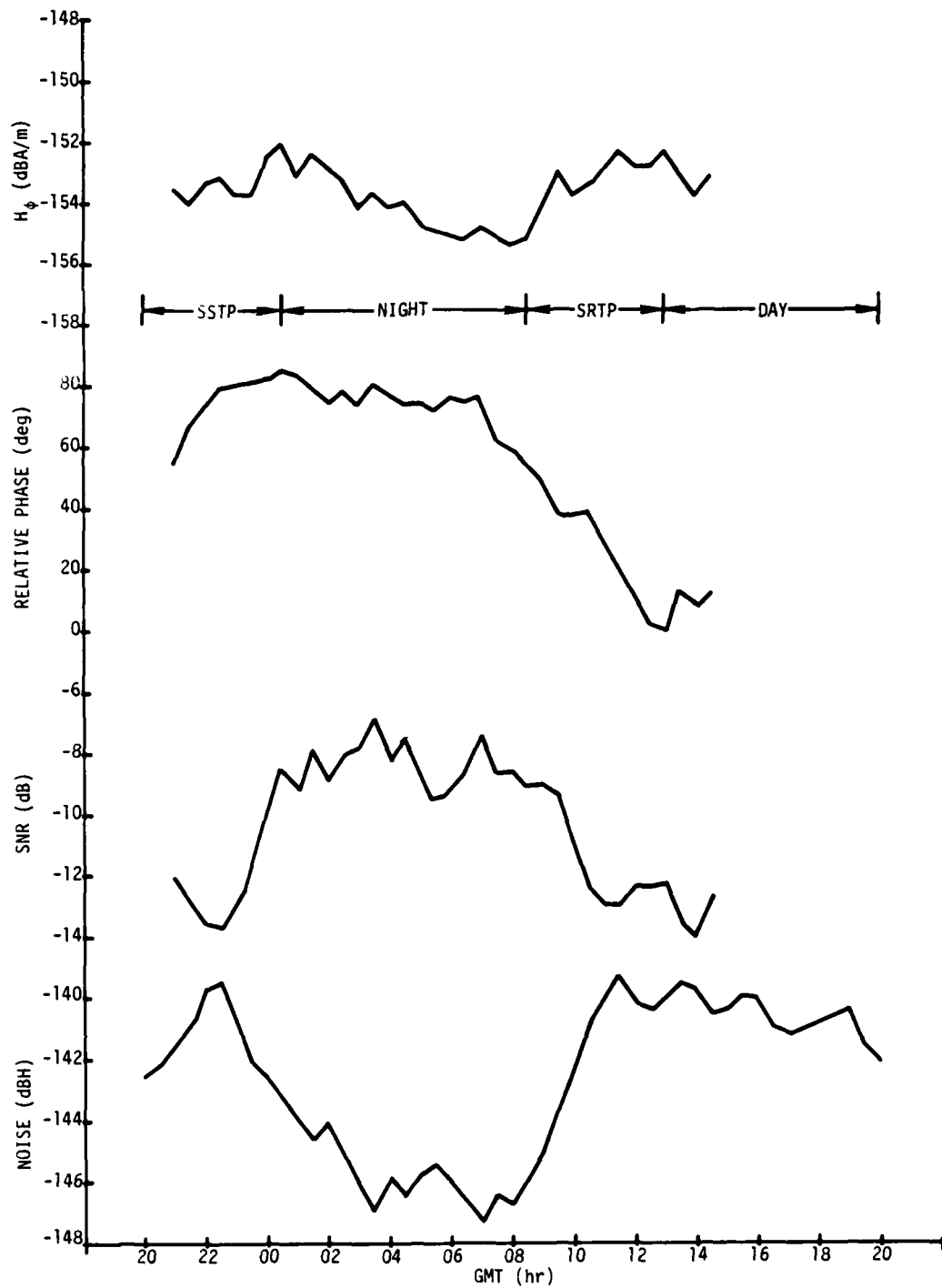


Figure B-18. North-Atlantic-Area Submarine Data Versus GMT, 18 and 19 February 1978

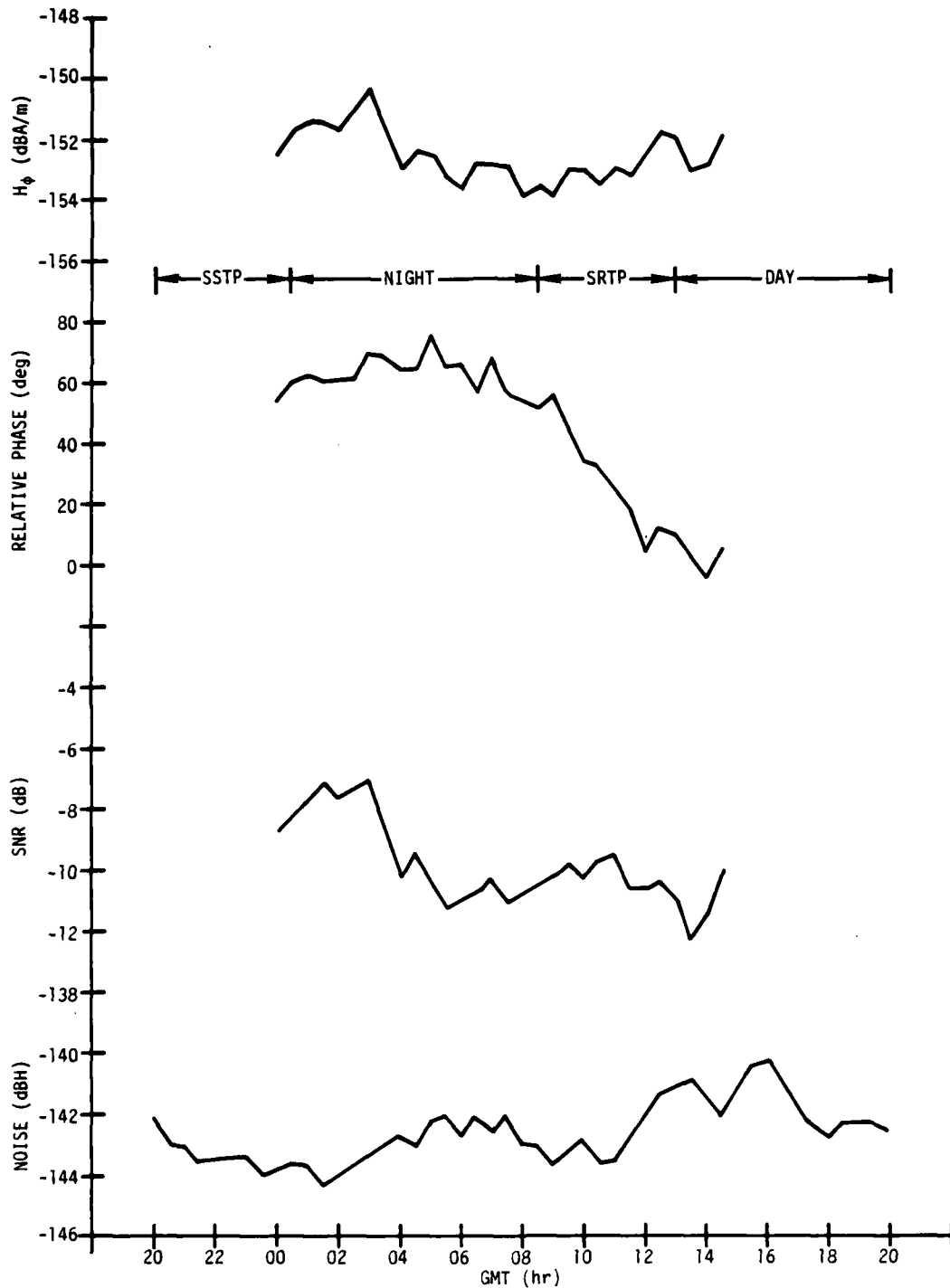


Figure B-19. North-Atlantic-Area Submarine Data Versus GMT, 19 and 20 February 1978

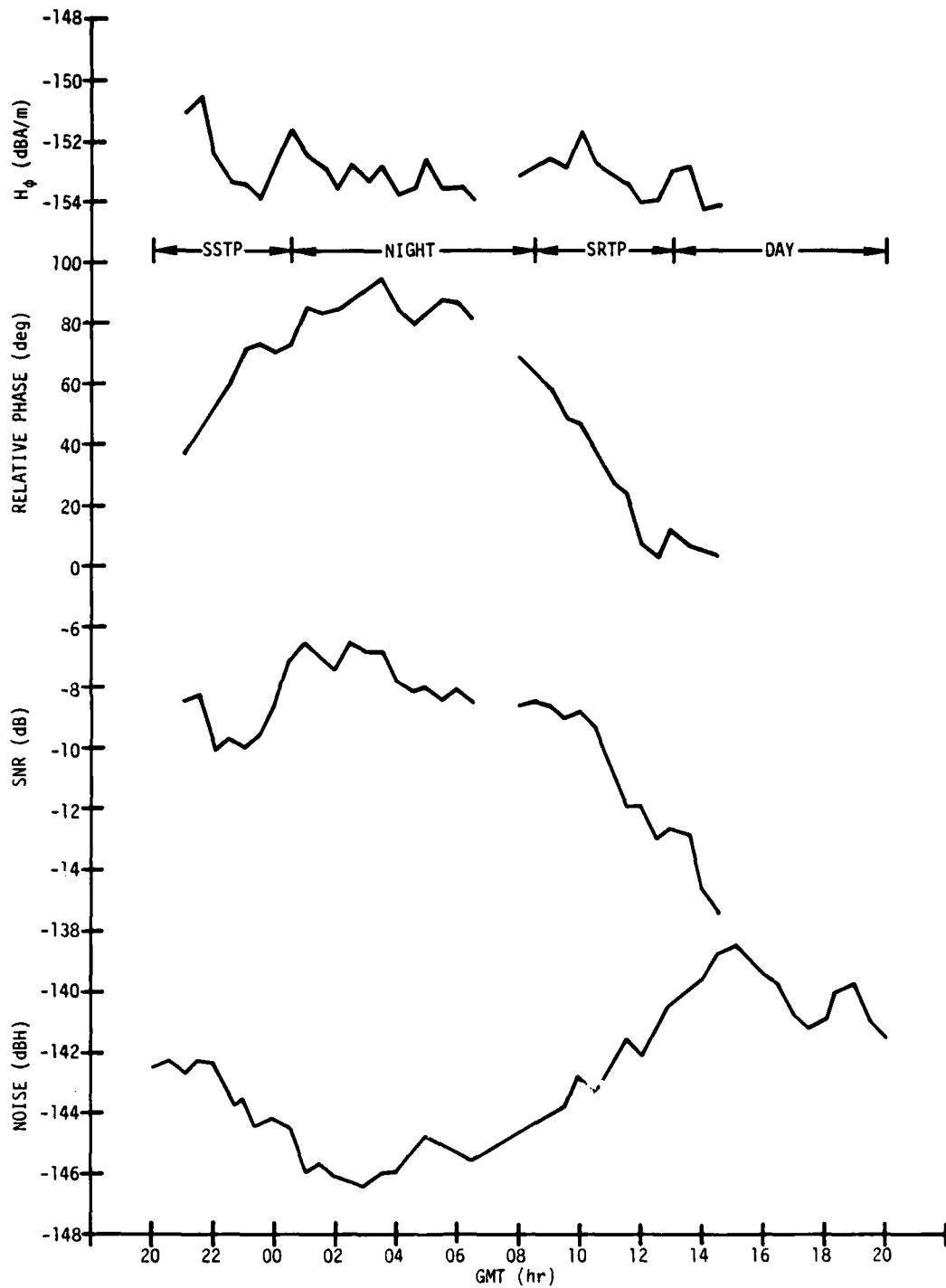


Figure B-20. North-Atlantic-Area Submarine Data Versus GMT, 20 and 21 February 1978

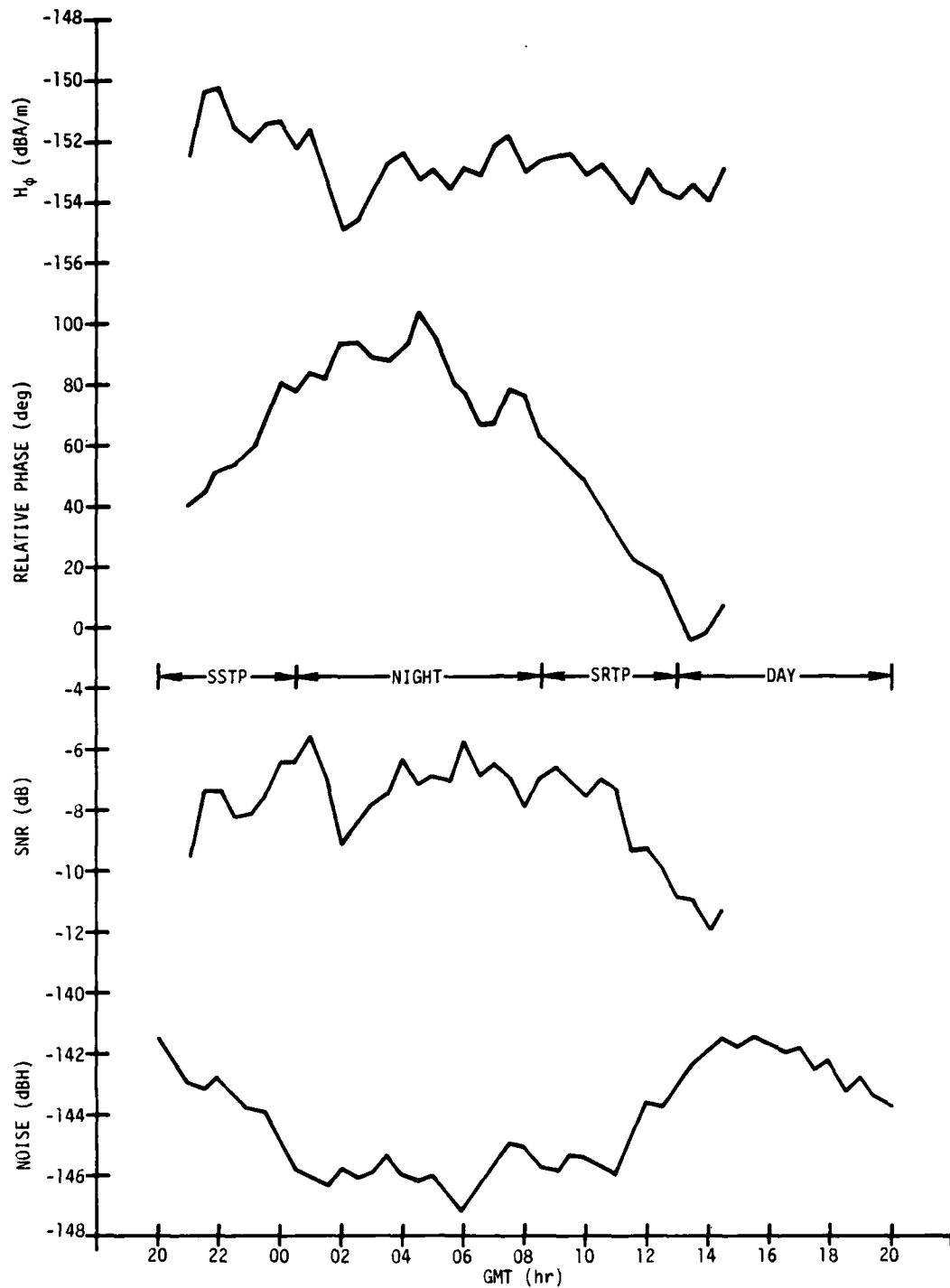


Figure B-21. North-Atlantic-Area Submarine Data Versus GMT, 21 and 22 February 1978

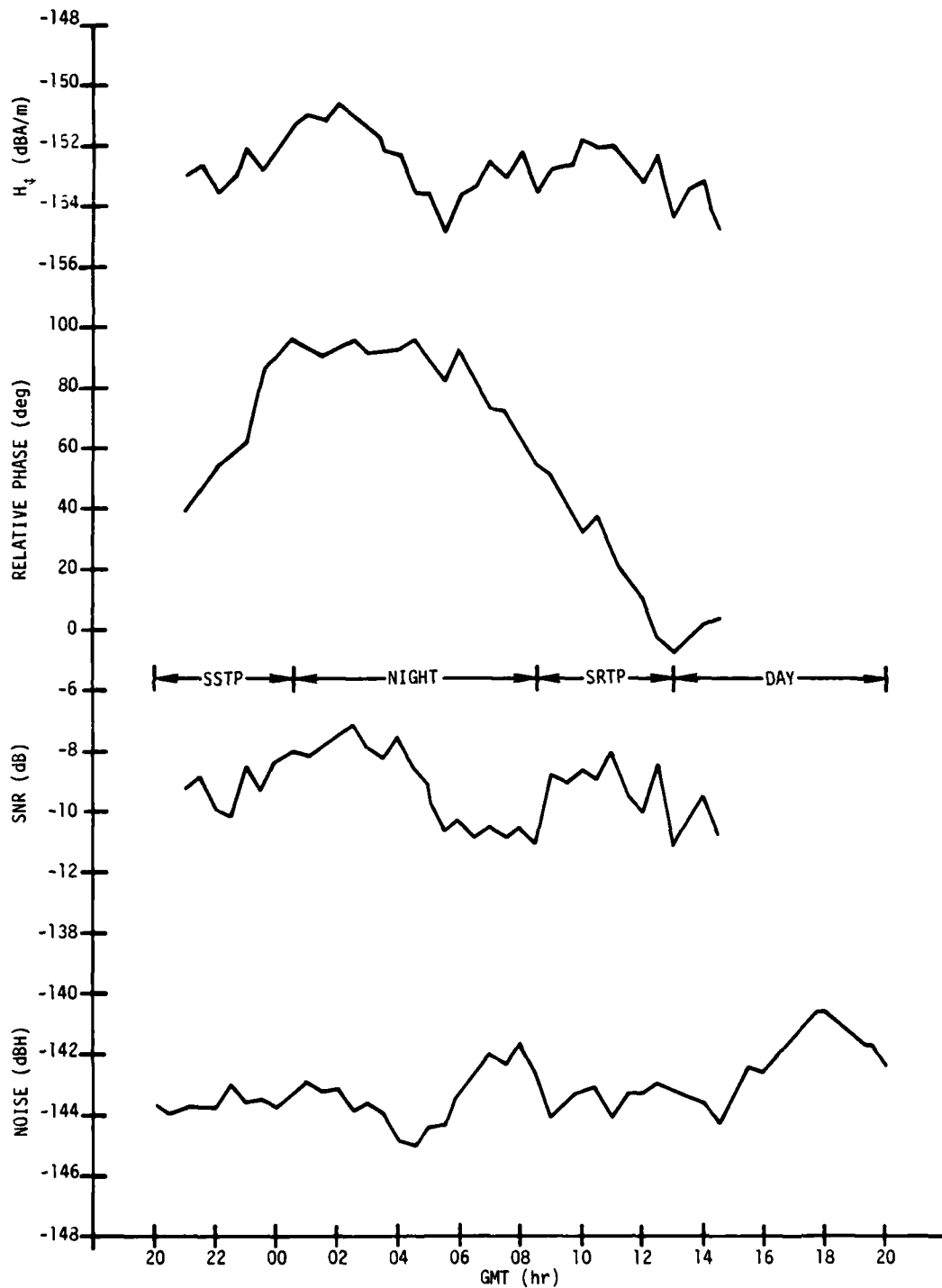


Figure B-22. North-Atlantic-Area Submarine Data Versus GMT, 22 and 23 February 1978

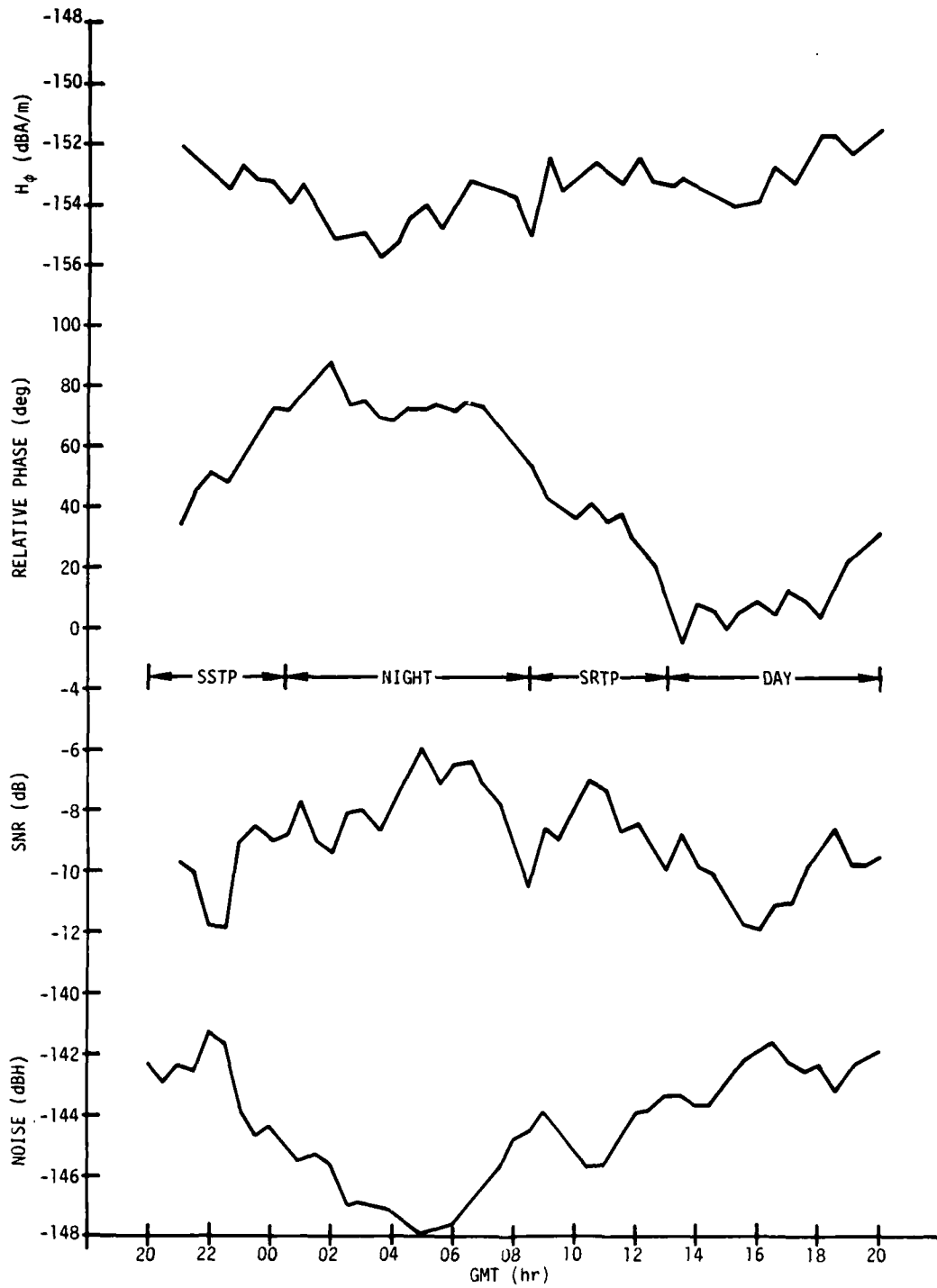


Figure B-23. North-Atlantic-Area Submarine Data Versus GMT, 23 and 24 February 1978



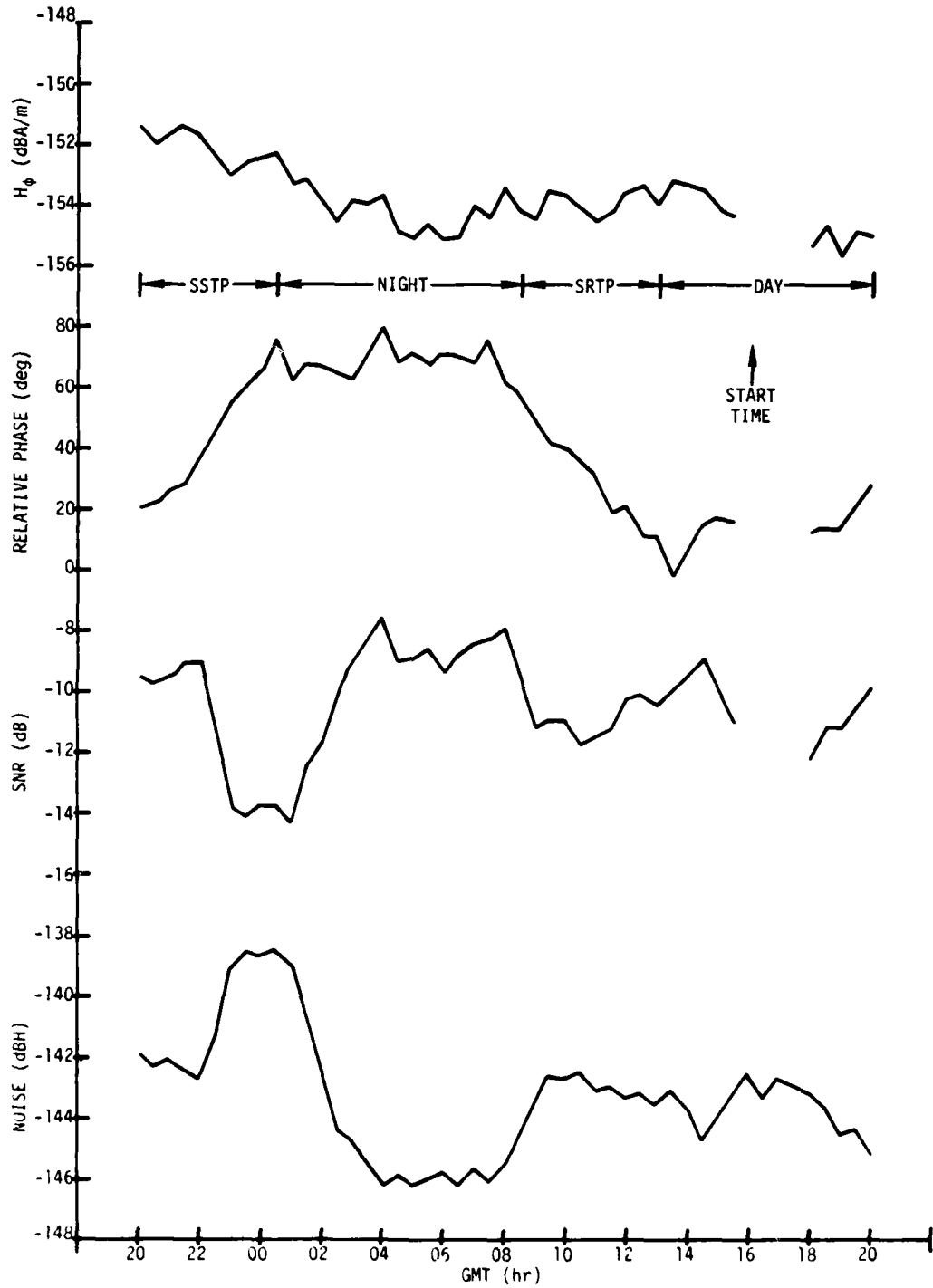


Figure B-24. North-Atlantic-Area Submarine Data Versus GMT, 24 and 25 February 1978

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