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ELF PVS Field Strength Measurements, October 1977

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Preface

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From September 1976 to December 1978, extremely low frequency (ELF) field-strength and effective-noise measurements were taken aboard operational submarines. The results of measurements taken in Connecticut and aboard two submarines during October 1977 are discussed. The principal test result is that the average field strengths measured aboard the two submarines (one located in the North Atlantic and one located in the Western Pacific) are in excellent agreement with previous ELF measurements taken over similar paths.

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GLOSSARY OF ABBREVIATIONS

ELF	Extremely low frequency
EW	East-west
GMT	Greenwich Mean Time
MPTV	Maximum peak-to-trough variation
MSK	Minimum shift keying
NS	North-south
NUSC	Naval Underwater Systems Center
PVS	Propagation validation system
SNR	Signal-to-noise ratio
SRTP	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, OCTOBER 1977

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.[1] 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 early October 1977, one submarine involved in testing 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. 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 October 1977 submarine field-strength measurements and will compare them with simultaneous measurements taken in Connecticut.

OCTOBER 1977 NORTH-ATLANTIC-AREA RESULTS

During this time period, data were obtained on 9 days from the North-Atlantic-area submarine and from the Connecticut site on 29 days. The daily plots of signal strength, effective noise,* and SNR versus Greenwich Mean Time (GMT) are presented in appendix A for North-Atlantic-area submarine data and in appendix B for Connecticut data.

The WTF antenna phasing angle (ψ) was 291 deg from 2 through 17 (and on 31) October, and 21 deg from 18 to 30 October. The WTF transmitting frequency was 76 ±4 Hz.

Presented in table 1 are the October 1977 North-Atlantic-area submarine daily field-strength averages. These data are broken up into four time periods, which should be representative of

1. Nighttime propagation conditions (~0030 to 0800 GMT),

2. Sunrise transition period (SRTP) propagation conditions (~0800 to 1230 GMT),

3. Daytime propagation conditions (~1230 to 2100 GMT), and

4. Sunset transition period (SSTP) propagation conditions (~2100 to 0030 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 sometimes changes by 2 to 4 dB from one day to the next. This phenomenon is typical of ELF propagation on northern-latitude paths.[3,4]

The 6 through 15 October average field-strength, SNR, and effective-noise values are plotted in figure 1† versus GMT. From this figure, we see that the highest field strengths were measured during the 1430 to 1630 GMT daytime period, 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 8 dB with the minimum values measured during the early

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

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

Table 1. October 1977 North-Atlantic-Area Submarine Daily Field-Strength Averages

Date	Night H_ϕ (dBA/m)	SRTP H_ϕ (dBA/m)	Day H_ϕ (dBA/m)	SSTP H_ϕ (dBA/m)	Relative Phase (deg)
10/6	-	-	-	-152.0	-
10/7	-151.9	-150.9	-151.1	-151.2	56.5
10/8	-153.5	-151.6	-151.3	-151.6	37.0
10/9	-153.1	-150.7	-151.4	-151.1	64.8
10/10	-152.3	-151.3	-151.4	-151.3	-
10/11	-152.7	-151.5	-152.1	151.0	61.5
10/12	-154.3	-152.3	-	-152.1	64.3
10/13	-151.8	-152.2	-152.6	-153.3	61.8
10/14	-154.2	-153.5	-153.1	-152.9	57.0
10/15	-154.4	-	-	-	60.8
Monthly Average	-153.1	-151.8	-151.7	-151.8	60.5

morning hours (0400 to 0800 GMT) and the maximum values measured during the late-afternoon/early-evening hours (1900 to 2100 GMT).

A plot of the October 1977 North-Atlantic-area SNR distribution (N = 269 30-min samples) is presented in figure 2. From this curve, we see that the predetection (in a 1-Hz bandwidth) SNR at optimum heading was greater than -7 dB 50 percent of the time and greater than -12 dB 98 percent of the time. The postdetection SNR (after 30-min integration time) was greater than 25.5 dB 50 percent of the time and greater than 20.5 dB 98 percent of the time.

During January, March, and April 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.[5,6,7] These values are consistent with previous measurements taken over similar paths.[8,9]

Referring to table 1, we see that the average October North-Atlantic-area (~4.5 Mm from WTF) daytime, transition-period, and nighttime measured field strengths were -151.7, -151.8, and -153.1 dBA/m, respectively. Based on the abovementioned values of attenuation rate and excitation factor, the predicted field strengths at a range of 4.5 Mm are -151.8, -152.4, and -153.1 dBA/m, respectively. Note that there is excellent agreement between the measured and predicted North-Atlantic-area daytime and nighttime field strengths. On the other hand, the measured transition-period field strengths were approximately 0.5 dB greater than predicted.

At the Connecticut site, the measured average difference in relative phase (Δφ) between the nighttime and daytime periods during 7 to 15 October was 21.5 deg. Thus, the average relative-phase velocity difference between daytime and nighttime propagation conditions [Δ(c/v)] was 0.15 during 7 to 15 October.

Referring again to table 1, we see that for 7 of 8 days the North-Atlantic-area average measured Δφ variation was remarkably stable (i.e., 60.5 ±4 deg). For a range of 4.5 Mm, this translates to Δ(c/v) = 0.15, which is identical to the value inferred from the Connecticut measurements alone.

On several occasions during the past decade, the 40 to 80 Hz ELF nighttime field strength measured at sites in the northeastern United States (i.e., Connecticut and Maryland) has displayed rapid decreases of from 4 to 8 dB in several hours. These severe nighttime disturbances sometimes occur during the several days following magnetic storms when similar but less-pronounced behavior is found to coincide with phase disturbances on very low frequency (VLF) paths across the northern United States.

We have shown[10,11] that the Connecticut nighttime field-strength amplitude was usually at a minimum between 0400 and 0800 GMT, whereas the nighttime relative phase was at a maximum approximately 1 hr earlier. The time of the lowest nighttime field strengths coincides with the farthest south displacement of the auroral oval and, presumably, indicates the time at which energetic electrons would reach their southernmost point in the middle latitudes.

We have recently shown[5,6,12] that these localized ELF nighttime propagation anomalies are not restricted to measurement locations in the northeastern United States. Some additional examples of the similarity (in both amplitude and relative phase) of the Connecticut and North-Atlantic-area anomalous nighttime field strengths are presented in figures 3 through 6. These data are characterized by

1. Substantial amplitude decreases during the nighttime period of 0200 to 0600 GMT, with the relative phase peaking about an hour before the minimum nighttime amplitude time, and

2. Substantial amplitude increases and relative-phase decreases (and then increases) near the end of the nighttime measurement period and the beginning of the sunrise transition period (0600 to 1000 GMT).

A comparison of the 8 October 1977 Connecticut and North-Atlantic-area field strengths is presented in figure 3. During 8 October, the average North-Atlantic-area Δφ variation was only 37 deg compared to 60.5 ±4 deg for the other seven days measured (see table 1). On the other hand, the average Connecticut Δφ was approximately equal to the monthly average (~21 deg).

Referring to figure 3, we see that from approximately 0200 to 0530 GMT the amplitude steadily decreased 4 to 5 dB at both locations, while the relative phase peaked at 0430 GMT. Then, the amplitude steadily increased 4 to 5 dB from 0500 to 0800 GMT, while the 0430 to 0700 GMT relative phase decreased ~25 deg in Connecticut and ~40 deg in the North Atlantic. From 0700 to 1000 GMT, the relative phase increased ~18 deg in Connecticut and ~25 deg in the North Atlantic, while the 0800 to 1000 GMT amplitude decreased ~1 dB. The Connecticut relative phase then decreased to its normal daytime value around WTF sunrise. However, the North-Atlantic-area relative phase did not start decreasing until WTF sunrise and did not reach its normal daytime value until 2 hr later.

A comparison of the 9 October 1977 Connecticut and North-Atlantic-area field strengths is presented in figure 4. From ~0300 to 0530 GMT, the field strength at both locations rapidly decreased 4 to 5 dB, while the relative phase peaked a half hour before the minimum nighttime amplitude time. The ~0500 to 0630 GMT relative phase then decreased ~30 deg in Connecticut and ~40 deg in the North Atlantic before increasing ~15 deg by 0900. Meanwhile, the 0600 to 0900 GMT field strength rapidly increased 4 to 5 dB at both locations.

Presented in figure 5 is a comparison of the 11 October 1977 Connecticut and North-Atlantic-area field strengths. From WTF sunset to 0430 GMT, the field strength decreased ~4 dB at both locations. During the next hour, the Connecticut amplitude increased by ~1 dB, while the North-Atlantic amplitude further decreased by ~2 dB. From 0530 to 0800 GMT, the Connecticut field strength gradually increased ~2.5 dB, while the North-Atlantic field strength rapidly increased 6 dB.

The North-Atlantic-area relative phase peaked 1 hr before the minimum nighttime amplitude time, decreased ~25 deg from 0430 to 0630, then increased ~30 deg from 0630 to 0830 before decreasing to the normal daytime value by WTF sunrise. The Connecticut relative phase peaked 2 hr before the minimum amplitude time, then steadily decreased 20 deg from 0230 to 0700. The relative phase then increased ~10 deg from 0700 to 0830 before dropping to the normal daytime value by WTF sunrise.

A comparison of the 12 October 1977 Connecticut and North-Atlantic-area field strengths is presented in figure 6. From WTF sunset to ~0530, the field strength at both locations decreased 5 to 6 dB, while the relative phase peaked a half hour before the minimum nighttime amplitude time. From ~0530 to WTF sunrise, the Connecticut field strength increased ~7 dB, while the North-Atlantic field strength increased ~5 dB. Meanwhile, at both locations, the relative phase decreased 20 to 25 deg by 0600, then increased 10 to 20 deg by 0900, before decreasing to the normal daytime value by WTF sunrise.

EARLY-OCTOBER 1977 WESTERN-PACIFIC-AREA RESULTS

During this time period, data were obtained on 16 days from the Western-Pacific-area submarine, which was located approximately 11.5 Mm from WTF. The daily plots of signal strength, effective noise, and SNR versus GMT are presented in appendix C.

The WTF antenna phasing angle (ψ) was 291 deg from 30 September through 17 October and the transmitting frequency was 76 ±4 Hz.

Presented in table 2 are the early-October 1977 Western-Pacific-area submarine daily field-strength averages. These data are broken up into four time periods which should be representative of

1. Nighttime propagation conditions (~0830 to 1230 GMT),

2. SRTP propagation conditions (~1230 to 2030 GMT),

3. Daytime propagation conditions (~2030 to 0030 GMT), and

4. SSTP propagation conditions (~0030 to 0830 GMT).

Referring to table 2, we see that two things immediately stand out:

1. The average field strengths measured from 30 September to 5 October are lower than those measured from 7 to 17 October (by 1 dB during the day, 1.5 dB during SRTP, and 2.5 dB at night), and

2. The average nighttime field strength measured within each of the abovementioned time periods is remarkably stable from one night to the next.

The main reason for the difference in field strengths is that the submarine was located at different ranges during the two time periods. From 30 September to 5 October that range was ~12 Mm from WTF, while from 7 to 17 October the range was ~11 Mm from WTF.

The 30 September to 17 October average field-strength (both amplitude and relative phase), SNR, and effective-noise values are plotted in figure 7 versus GMT. From this figure, we see that the highest field strengths were measured during the 0900 to 1000 GMT nighttime period, while the lowest field strengths were measured during the 2100 to 2200 daytime period (i.e., 12 hr later). The average daily effective-noise variation was approximately 7 dB, with the minimum values measured from 0200 to 0400 GMT and the maximum values measured from 0800 to 1000 and 1800 to 2000 GMT.

A plot of the early-October 1977 Western-Pacific-area SNR distribution (N = 487 30-min samples) is presented in figure 8. From this curve, we see that the predetection (in a 1-Hz bandwidth) SNR at optimum heading was greater than -14 dB 50 percent of the time and greater than -18 dB 90 percent of the time. The postdetection SNR (after 30-min integration time) was greater than 18.5 dB 50 percent of the time and greater than 14.5 dB 90 percent of the time.

From our previous measurements,[8,9] we have observed that, during daytime propagation conditions, the attenuation rate in the EW direction is approximately 0.3 dB/Mm greater than 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 dB during the day and -3.3 dB at night.[8,9,14]

Table 2. Early-October 1977 Western-Pacific-Area Submarine Daily Field-Strength Averages (ψ = 291 deg)

Date	Night H_ϕ (dBA/m)	SRTP H_ϕ (dBA/m)	Day H_ϕ (dBA/m)	SSTP H_ϕ (dBA/m)	Relative Phase (deg)
9/30	-159.9	-158.7*	-163.6	-158.6	137
10/1	-159.4	-160.0	-163.2	-159.4	155
10/2	-159.7	-160.0	-163.2	-160.7	167
10/3	-159.7	-161.0	-164.1	-160.3	159
10/4	-160.6	-160.8	-164.2	-162.2	154
10/5	-160.1	-161.1	-161.3*	-160.7	180
10/7	-157.2	-158.3	-162.1	-160.0	168
10/8	-157.2	-158.6	-161.4	-160.8	179
10/9	-157.7	-159.6	-160.9	-160.2	199
10/10	-157.4	-160.1	-162.7	-159.8	159
10/11	-158.0	-159.1*	-161.8	-160.5	177
10/12	-157.1*	-	-162.1	-162.2	184
10/13	-157.2	-158.0*	-164.2	-162.5	141
10/14	-157.2	-159.4	-163.7	-161.8*	-
10/15	-	-	-161.9	-162.3	-
10/17	-157.9*	-	-161.5	-159.3	142
Average	-158.3	-159.6	-162.6	-160.7	164

*Average of only two or three samples.

Based on an (unpublished) 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 apply also 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 that measured during March/April 1971.

Referring to table 2, we see that the average early-October 1977 Western-Pacific-area (~11.5 Mm from WTF) daytime, transition period, and nighttime field strengths were -162.6, -160.2, and -158.3 dBA/m, respectively. Based on the abovementioned values of 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 11.5 Mm are -162.7, -160.4, and -158.3 dBA/m, respectively, which are in excellent agreement with the measured field strengths.

Referring to table 2, we see that the average Western-Pacific-area $\Delta\phi$ variation was 164 deg. For a range of 11.5 Mm, this translates to a $\Delta(c/v)$ of 0.15 to 0.16, which is in excellent agreement with the 0.15 value inferred from both the Connecticut and North-Atlantic-area measurements.

As we previously mentioned, the 30 September to 5 October field strengths were lower than the 7 to 17 October field strengths because the range was greater (~12 Mm). The average 30 September to 5 March field strengths were -163.2 dBA/m during the day and -159.9 dBA/m at night. 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 dBA/m during the day and -159.7 dBA/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 30 September to 5 October 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 dBA/m. These are the same values of attenuation rate and excitation factor inferred from the May 1972 Alaska/Saipan measurements.[8,9]

Referring to figure 7, we see that the daytime field strength steadily decreased, minimized, and then steadily increased. This is further exemplified in figure 9, which is a plot of the 30 September to 8 October individual field-strength values for the period of 2000 to 2400 GMT. Here, we see that, during each of these days, the field strength decreased 6 dB from 2000 to 2130, then increased 5 dB from 2130 to 2400. The time of minimum field strength (~2130) is about 1 hr 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 variation (MPTV) in the interference pattern will be equal to the sum of the two waves divided by their difference. That is,

$$\mathrm{MPTV} = \left| \frac{e^{-\alpha_D \rho_D} + e^{-\alpha_R \rho_R}}{e^{-\alpha_D \rho_D} - e^{-\alpha_R \rho_R}} \right| , \qquad (1)$$

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 nepers) and $\alpha_R\rho_R$ = 28 dB (3.224 nepers). Inserting these values in equation (1) results in MPTV = 1.92 (5.7 dB), which is almost identical to the measured results of 5 to 6 dB.

The most unusual effective-noise variations measured on the Western-Pacific-area submarine occurred on 10 and 12 October. Presented in figure 10 are the 10, 11, and 12 October effective-noise values versus GMT. We see that, during 11 October, the peak-to-trough variation was ~11 dB. However, on both 10 and 12 October, the peak-to-trough variation was ~20 dB. During both days the effective noise decreased ~10 dB from 0200 to 0400 GMT, then increased 12 to 16 dB from 0400 to 0900 GMT.

Unfortunately, the WTF was not on the air from 0100 to 0700 GMT on 10 October. However, it was on the air during this time on 12 October. Presented in figure 11 are the 12 October 1977 Western-Pacific-area data versus GMT. During the daytime period, the average field strength was about the same as the monthly average. However, during the SSTP (when the WTF was in darkness and the Western-Pacific area in daylight), the field strength increased ~4 dB from 0100 to 0300 GMT, rapidly decreased ~6 dB from 0400 to 0630 GMT, then very rapidly increased ~9 dB from 0700 to 0830 GMT (the beginning of the nighttime propagation period). Meanwhile, except for a slight dip around 0500 GMT, the relative phase steadily increased ~170 deg from 0100 to 0900.

During the 2-hr period of 0330 to 0530 GMT, the predetection SNR (in a 1-Hz bandwidth) was greater than -4 dB (figure 11). Around 0400 GMT, the SNR was ~-1 dB, which corresponds to a postdetection SNR of +31.5 dB, an amazing fact considering that the submarine was located ~11.5 Mm from WTF!

In figures 3 through 6, we presented some examples of the similarity (in both amplitude and relative phase) of the Connecticut and North-Atlantic-area anomalous nighttime field strengths. Presented in figures 12 and 13 are comparisons of the Connecticut, North-Atlantic, and Western-Pacific 0200 to 1000 GMT field strengths for the same dates (8, 9, 11, and 12 October). The transmitter, as well as the Connecticut site, was in total darkness from 0200 to 1000 GMT, as was the North-Atlantic-area site until 0800. On the other hand, the Western-Pacific-area site was not in total darkness until 0830 GMT.

The 8 and 9 October comparisons are presented in figure 12. The ⊙ at each location is the 0200 to 1000 GMT average monthly field-strength value at that location. Note that the 0400 to 1000 GMT field-strength plots are similar at all three locations. The time of minimum field-strength amplitude is 0530 GMT on 8 October and 0500 to 0530 GMT on 9 October. The difference between the minimum amplitude field strength and the 0200 to 1000 average monthly field strength was 3 to 4 dB at the Connecticut and North-Atlantic-area sites and 1.8 to 2.0 dB at the Western-Pacific site. The fact that (1) the field strength was at a minimum at approximately the same time at all three locations and (2) the null was deeper at the total-darkness sites indicates that the propagation anomaly occurred very near the WTF and caused the nighttime excitation factor to decrease.

In figure 13, we show the 11 and 12 October comparisons of the Connecticut, North-Atlantic, and Western-Pacific 0200 to 1000 field strengths. Again, the ⊙ at each location is the 0200 to 1000 average monthly field-strength value at that location. Here, we see that the correlation is only fair. On 11 October, the time of minimum amplitude occurred first in the Western Pacific (0300 GMT), next in Connecticut (0430 GMT), and last in the North Atlantic (0530 GMT). Conversely, on 12 October, the time of minimum amplitude occurred first in the North Atlantic (0500 GMT), next in Connecticut (0530 GMT), and last in the Western Pacific (0630 to 0700 GMT).

The 12 October difference between the minimum amplitude field strength and the 0200 to 1000 GMT average monthly field strength was greater than 4 dB at the Connecticut and North-Atlantic-area sites and greater than 6 dB at the Western-Pacific-area site. The 12 October magnetic storm probably caused these widespread anomalies.

LATE-OCTOBER 1977 WESTERN-PACIFIC-AREA RESULTS

During this time period, data were obtained on nine days from the Western-Pacific-area submarine, which was located approximately 8.5 Mm from WTF. The daily plots of signal strength, effective noise, and SNR versus GMT are presented in appendix C.

The WTF antenna phasing angle (ψ) was 21 deg from 22 to 29 October and 291 deg from 3 to 5 November. The transmitting frequency was 76 ±4 Hz.

Presented in table 3 are the late-October 1977 Western-Pacific-area submarine daily field-strength averages. These data are broken up into four time periods, which should be representative of

1. Nighttime propagation conditions (~0800 to 1230 GMT),

2. SRTP propagation conditions (~1230 to 2000 GMT),

3. Daytime propagation conditions (~2000 to 0030 GMT), and

4. SSTP propagation conditions (~0030 to 0800 GMT).

The 22 October to 5 November average field-strength (both amplitude and relative phase), SNR, and effective-noise values are plotted in figure 14 versus GMT. For comparison purposes, the 22 to 29 October data are normalized to a WTF antenna phasing of ψ = 291 deg.

From figure 14, we see that the highest field strengths were measured at the end of the nighttime and beginning of the SRTP (1200 to 1300 GMT) periods, while the lowest field strengths were measured 12 hr earlier at the end of the daytime and beginning of the SSTP (0000 to 0100 GMT) periods. The average daily effective-noise variation was only 5 dB, with the minimum values measured from 0200 to 0400 GMT and the maximum values measured from 1800 to 2100 GMT.

Table 3. Late-October 1977 Western-Pacific-Area Submarine Daily Field-Strength Averages (ψ = 21 deg)

Date	Night H_ϕ (dBA/m)	SRTP H_ϕ (dBA/m)	Day H_ϕ (dBA/m)	SSTP H_ϕ (dBA/m)	Relative Phase (deg)
10/22*	-156.5	-156.4	-	-156.9	-
10/23*	-154.4	-156.6	-	-157.5	95
10/25*	-154.4	-156.2	-	-156.9	-
10/26*	-156.7	-154.8	-	-158.0	111
10/27*	-155.3	-156.6	-157.5	-158.1	73
10/28*	-157.2	-156.6	-158.2	-157.1	92
10/29*	-153.7	-154.6	-157.7	-157.1	76
11/4†	-	-	-158.6	-158.1	113
11/5†	-156.1	-	-158.3	-158.5	108
Average	-155.4	-155.9	-158.0	-157.5	95

*Data normalized to ψ = 291 deg.
†ψ = 291 deg.

Referring to table 3, we see that the average late-October 1977 Western-Pacific-area (~8.5 Mm from WTF) daytime, transition period, and nighttime field strengths were -158.0, -156.7, and -155.4 dBA/m, respectively. Based on the previously mentioned values of 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 8.5 Mm are -158.1, -156.7, and -155.4 dBA/m, which are in excellent agreement with the measured field strengths.

From 22 to 29 October 1977, the average Connecticut variation was 19 deg, which corresponds to a $\Delta(c/v)$ of 0.13. Referring to table 3, we see that the average Western-Pacific-area variation during late October was 95 deg, which, for a range of 8.5 Mm, corresponds to a $\Delta(c/v)$ of 0.12. Note that the agreement is very good.

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 at two different ranges in the Western-Pacific area) during October

1977 are in excellent agreement with simultaneous measurements taken in Connecticut and with previous ELF measurements taken over similar paths.

Anomalous ELF nighttime field-strength variations were simultaneously observed at all three locations, while anomalous effective-noise variations were observed in the Western-Pacific area.

Around 0400 GMT on 12 October, the predetection SNR measured on the Western-Pacific-area submarine was ~-1 dB, which corresponds to a postdetection SNR of +31.5 dB, an amazing fact considering that the submarine was located approximately 11.5 Mm from WTF!

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

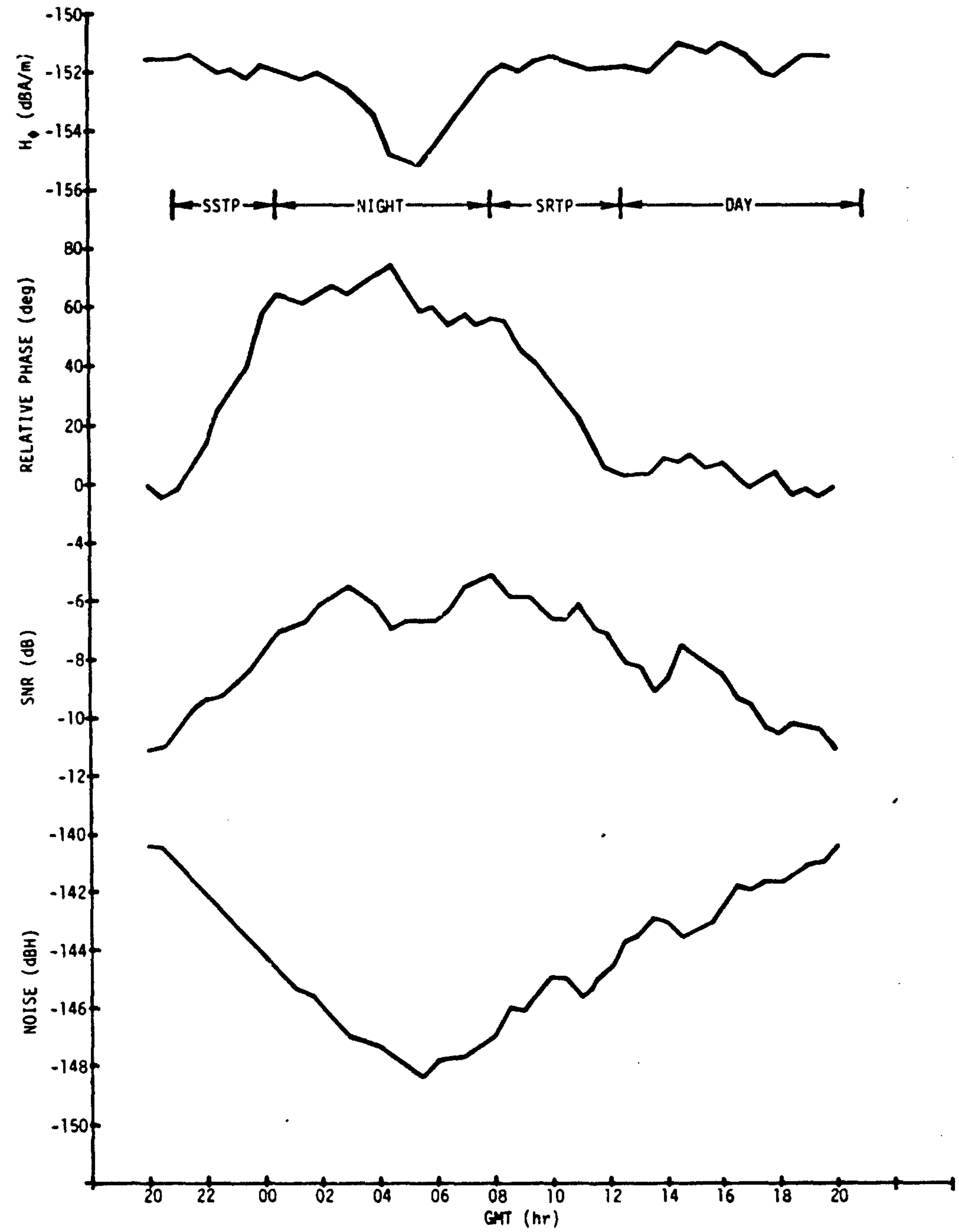

Figure 1. North-Atlantic-Area Average Data Versus GMT (ψ = 291 deg), 7 to 15 October 1977

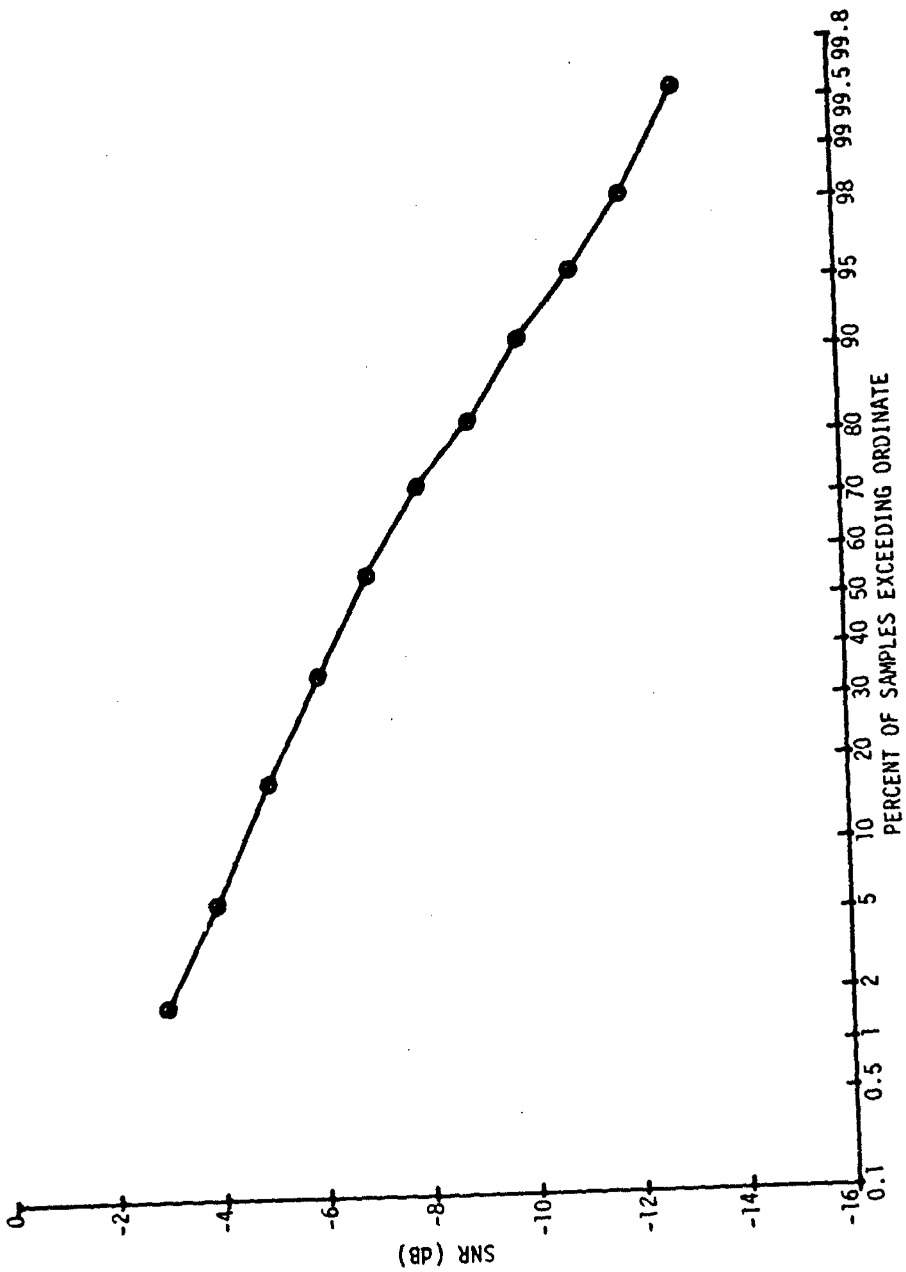

Figure 2. October 1977 North-Atlantic-Area SNR Distribution (N = 269)

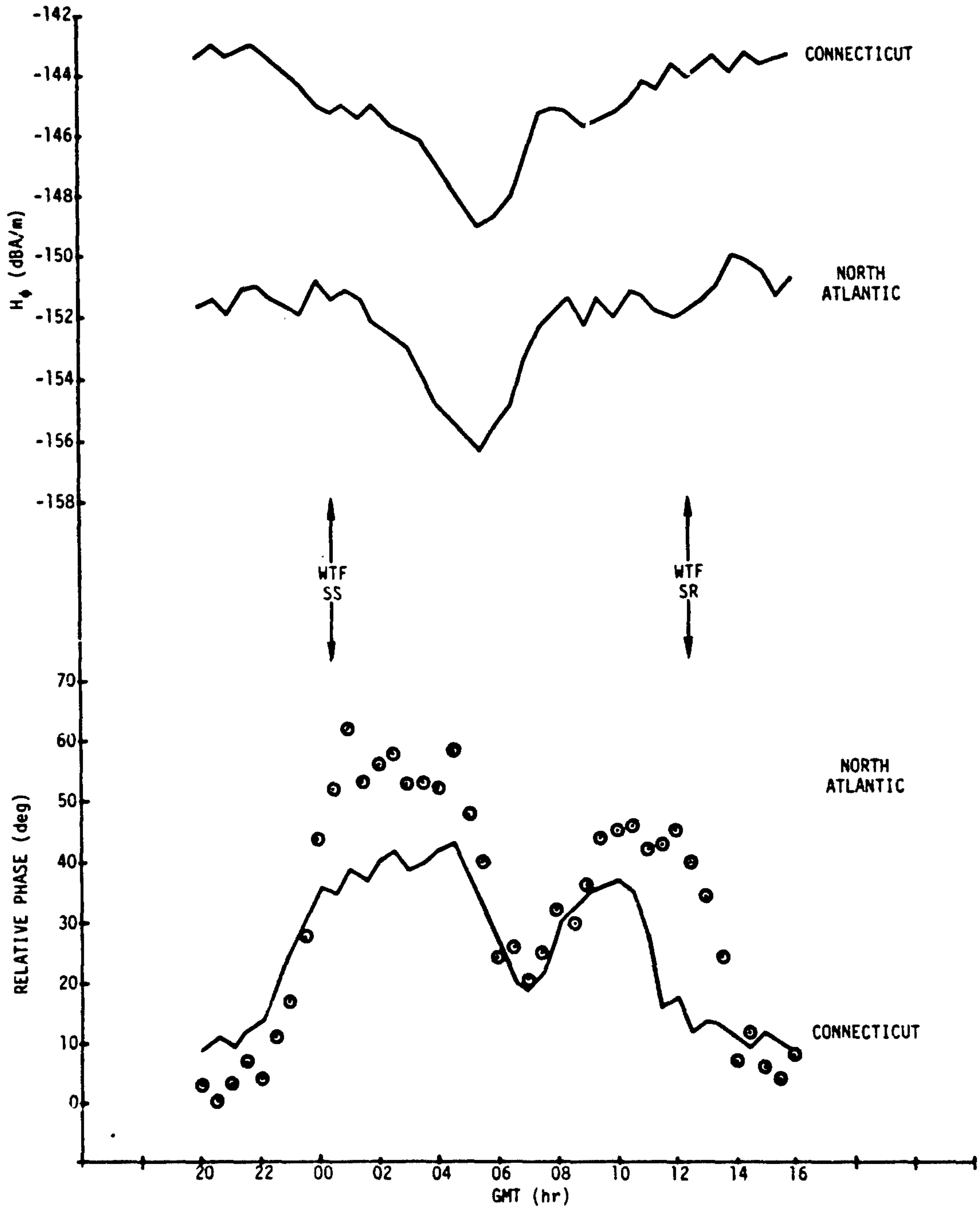

Figure 3. Comparisons of Connecticut and North-Atlantic-Area Field Strengths, 8 October 1977

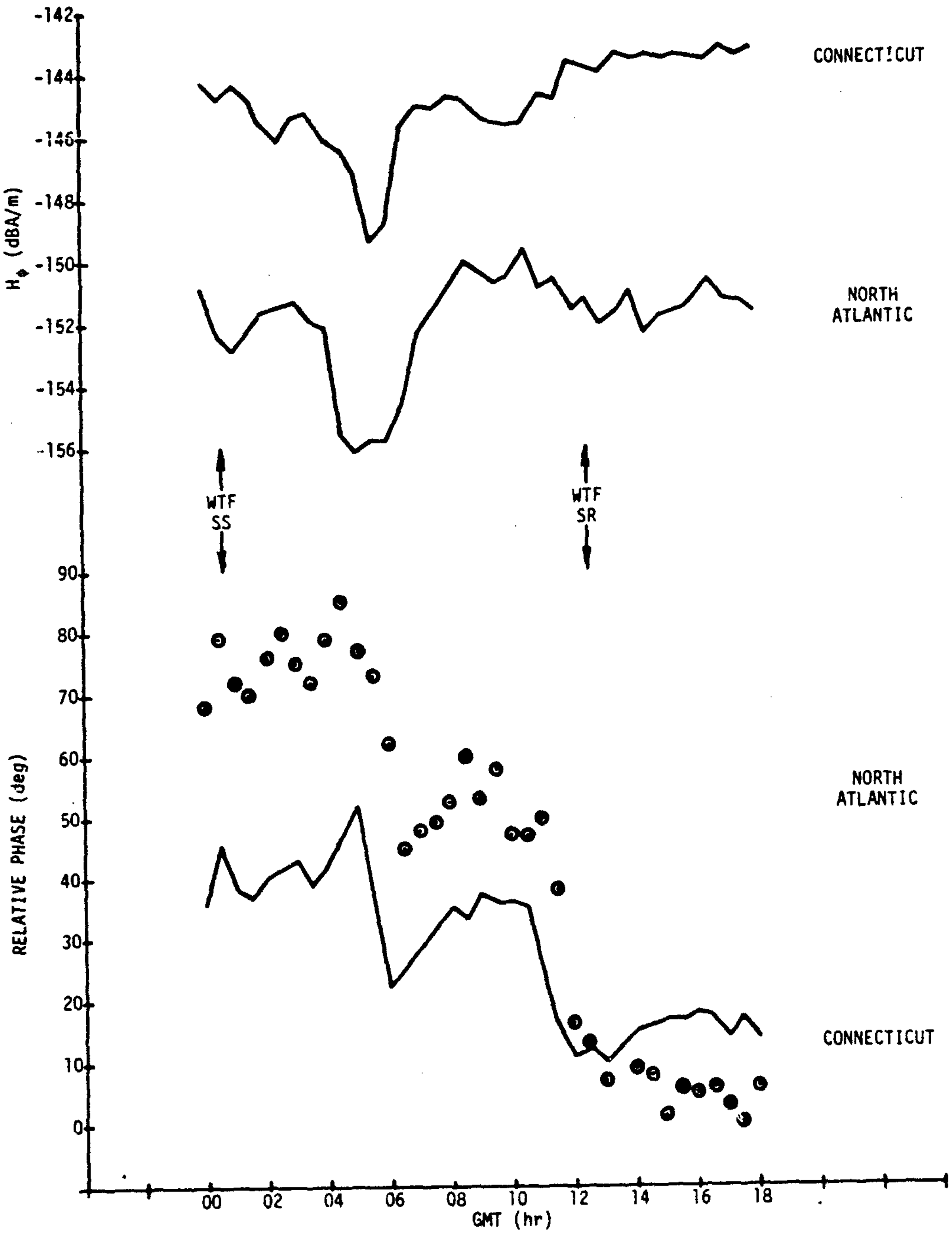

Figure 4. Comparisons of Connecticut and North-Atlantic-Area Field Strengths, 9 October 1977

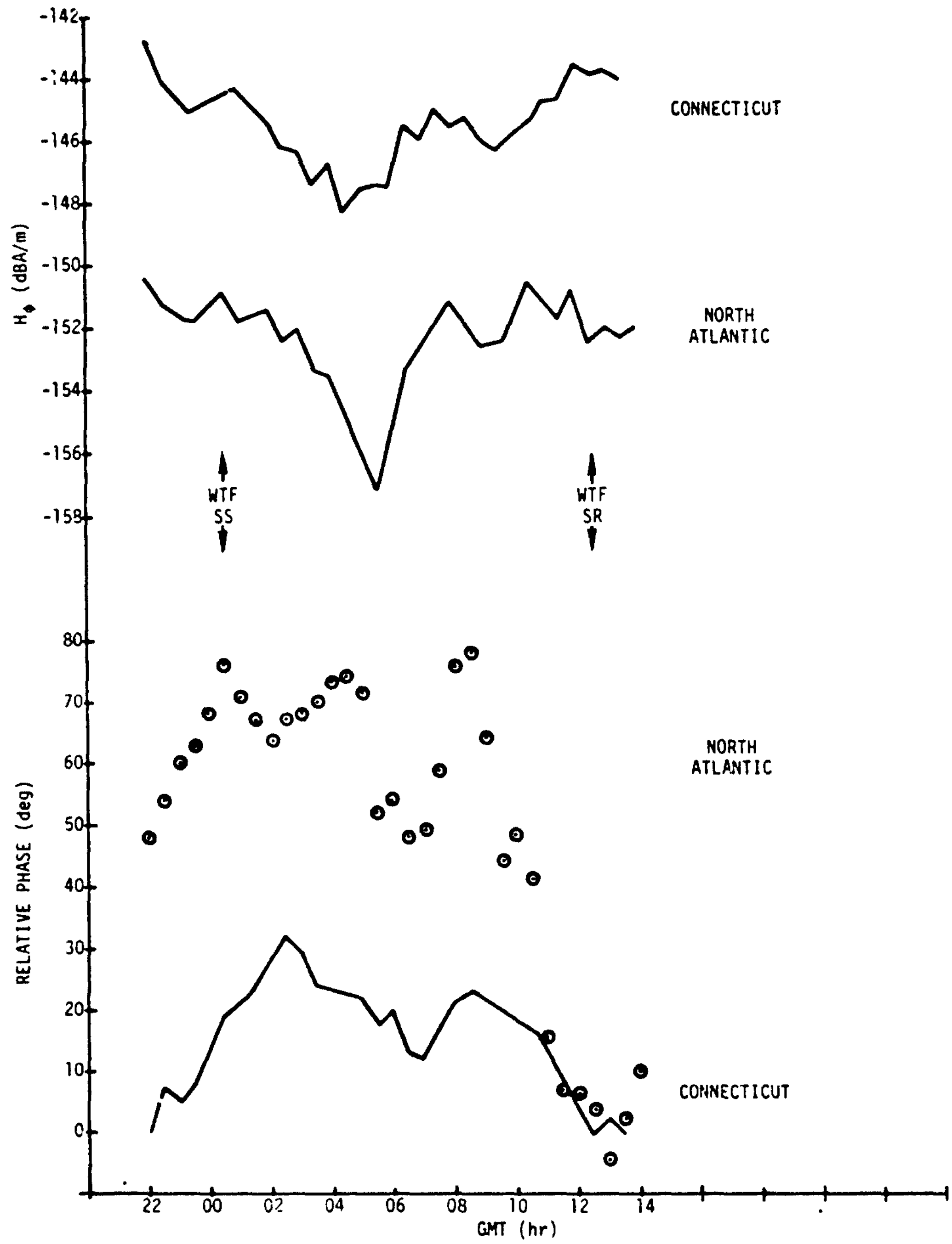

Figure 5. Comparisons of Connecticut and North-Atlantic-Area Field Strengths, 11 October 1977

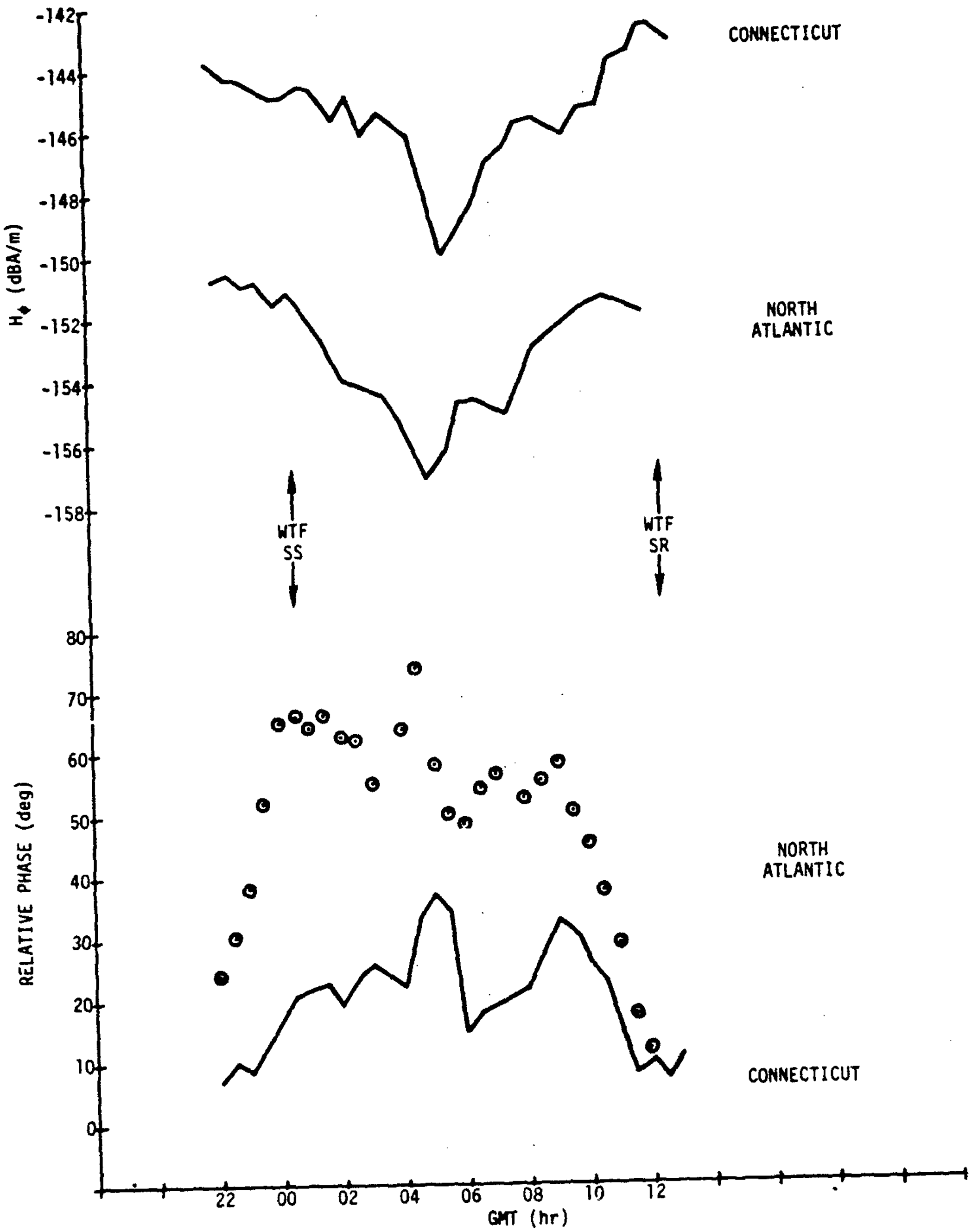

Figure 6. Comparisons of Connecticut and North-Atlantic-Area Field Strengths, 12 October 1977

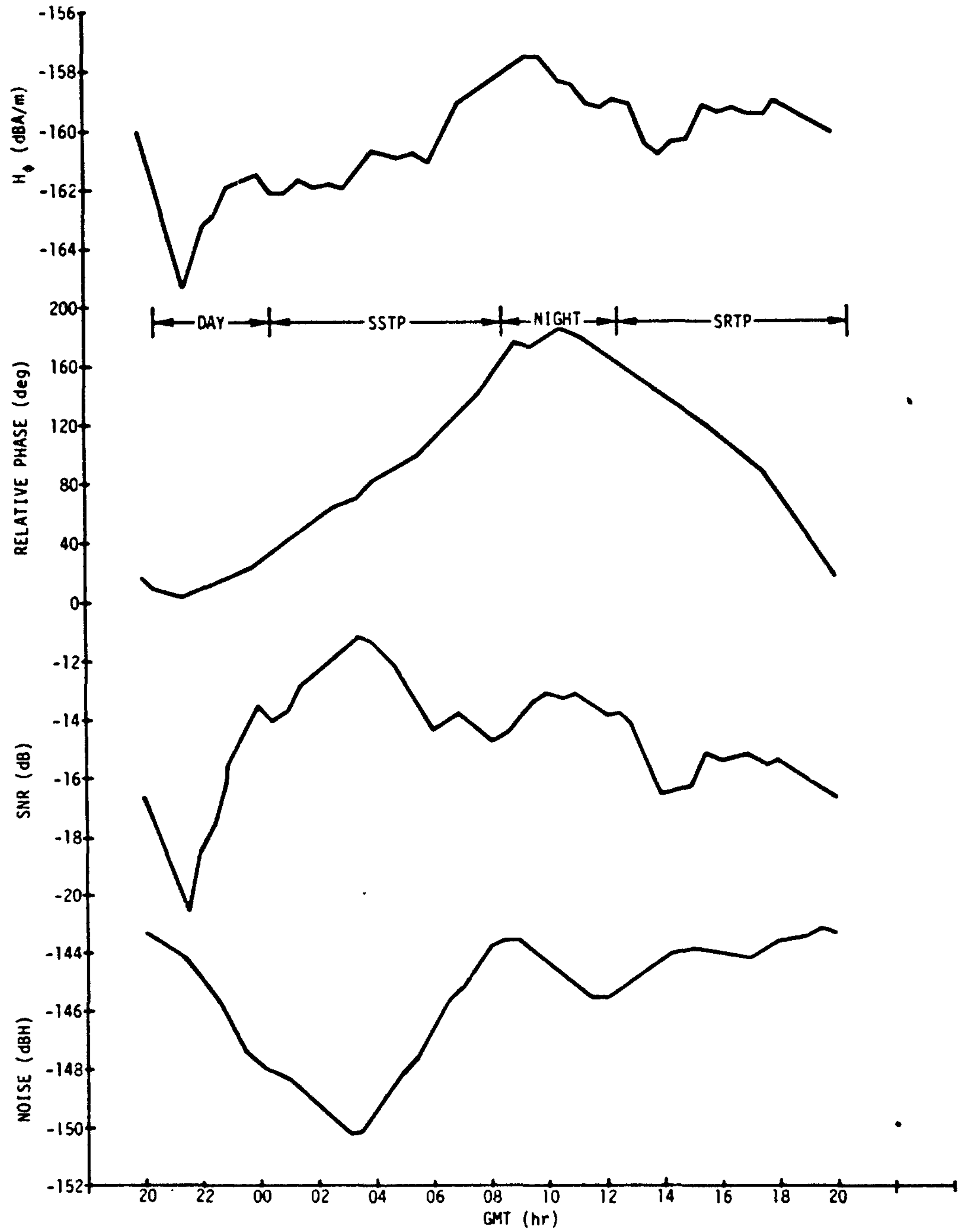

Figure 7. Western-Pacific-Area Average Data Versus GMT (ψ = 291 deg), 30 September to 17 October 1977

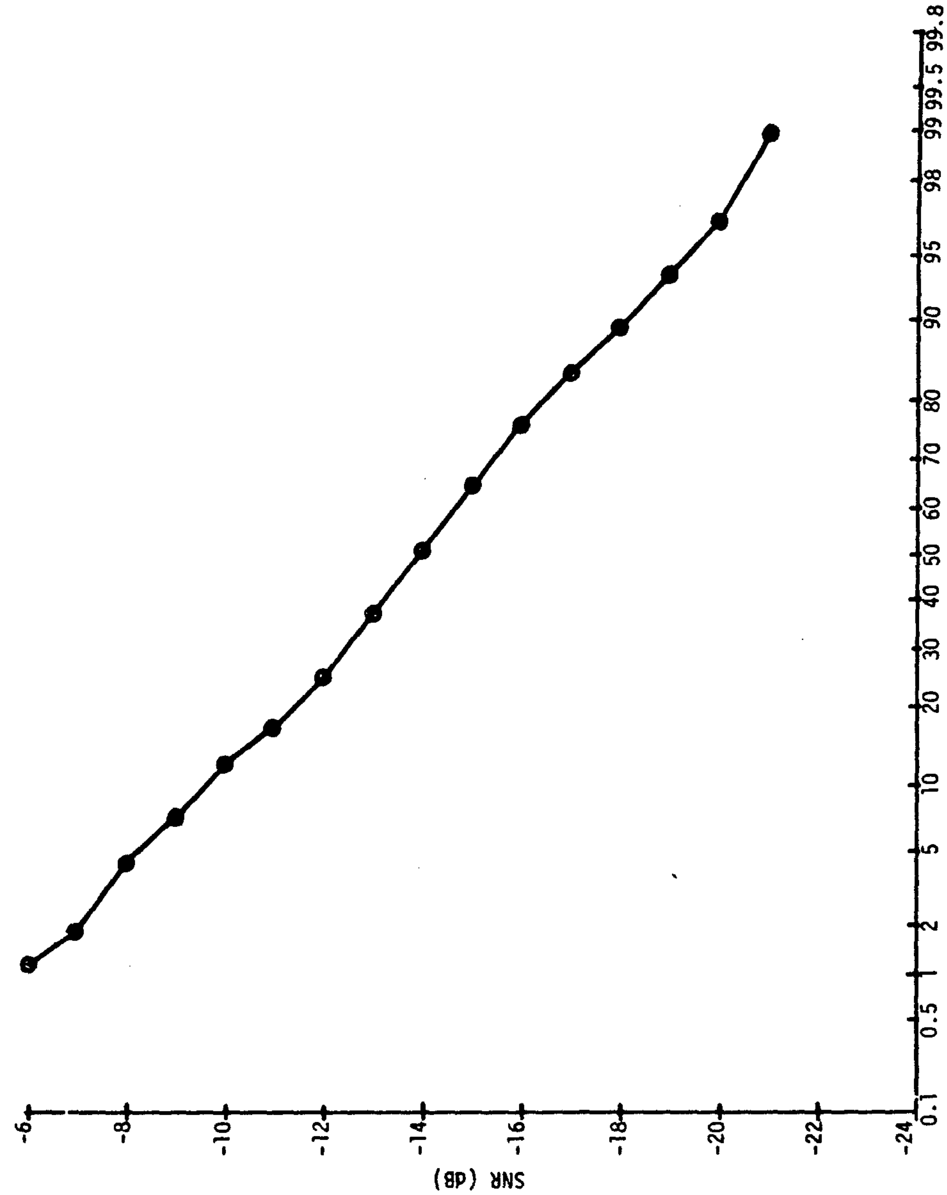

Figure 8. Early-October 1977 Western-Pacific-Area SNR Distribution (N = 487, ψ = 291 deg)

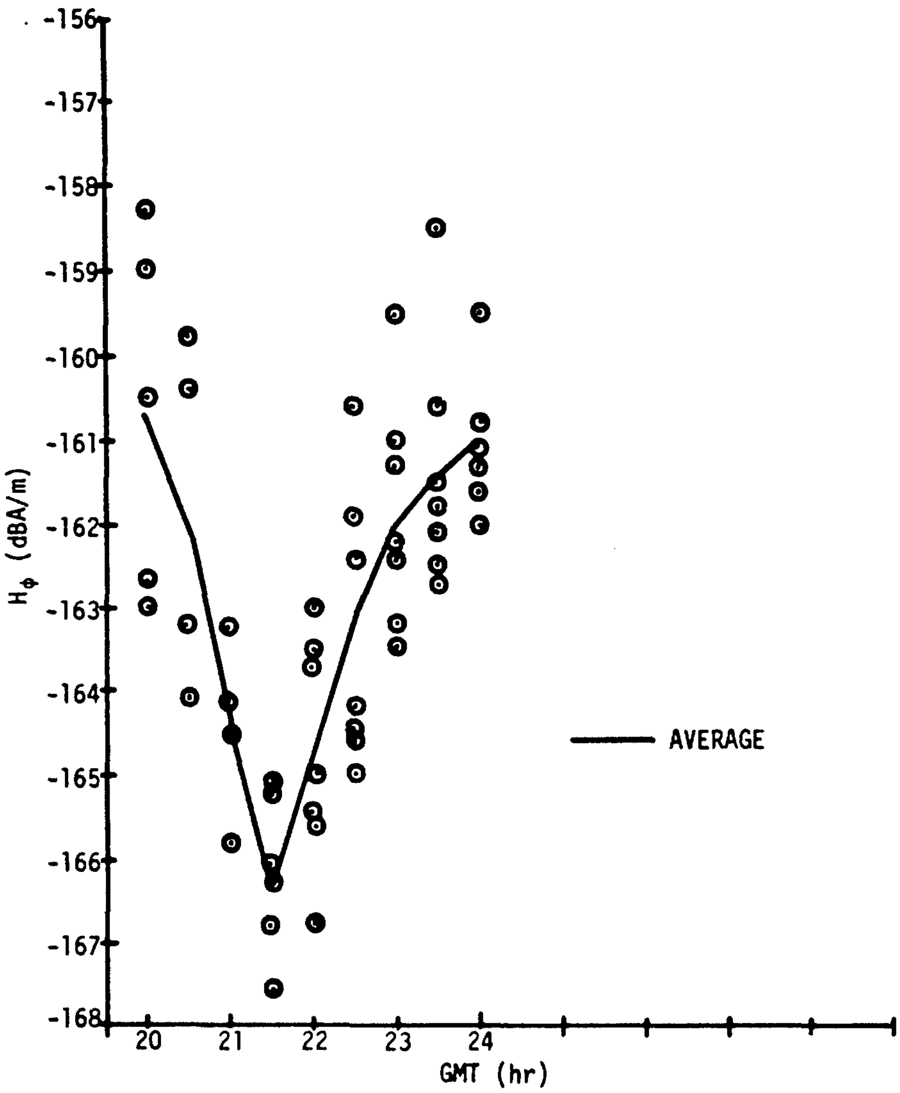

Figure 9. Field Strengths Versus GMT (2000 to 2400 GMT), 30 September to 8 October 1977

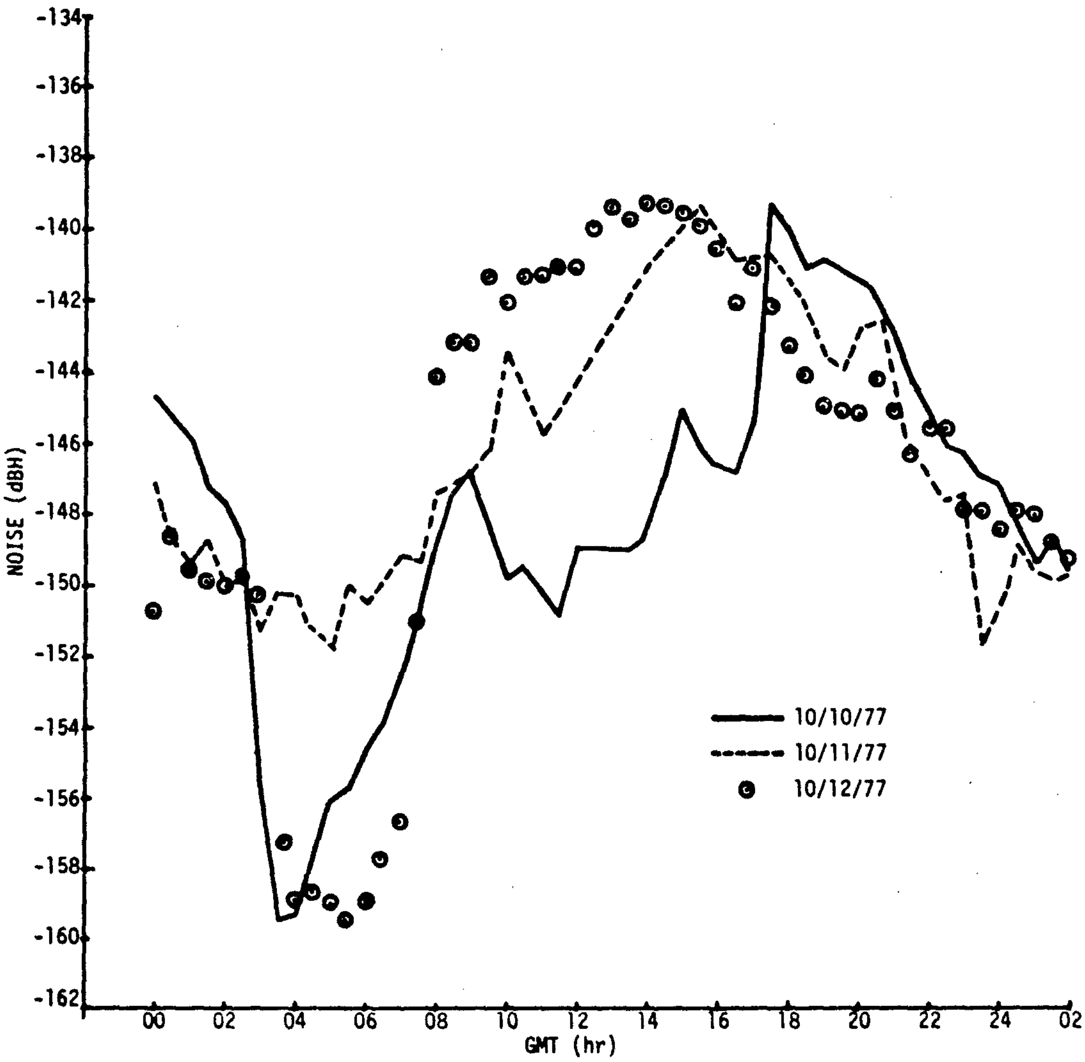

Figure 10. Western-Pacific-Area Effective Noise Versus GMT, 10 to 12 October 1977

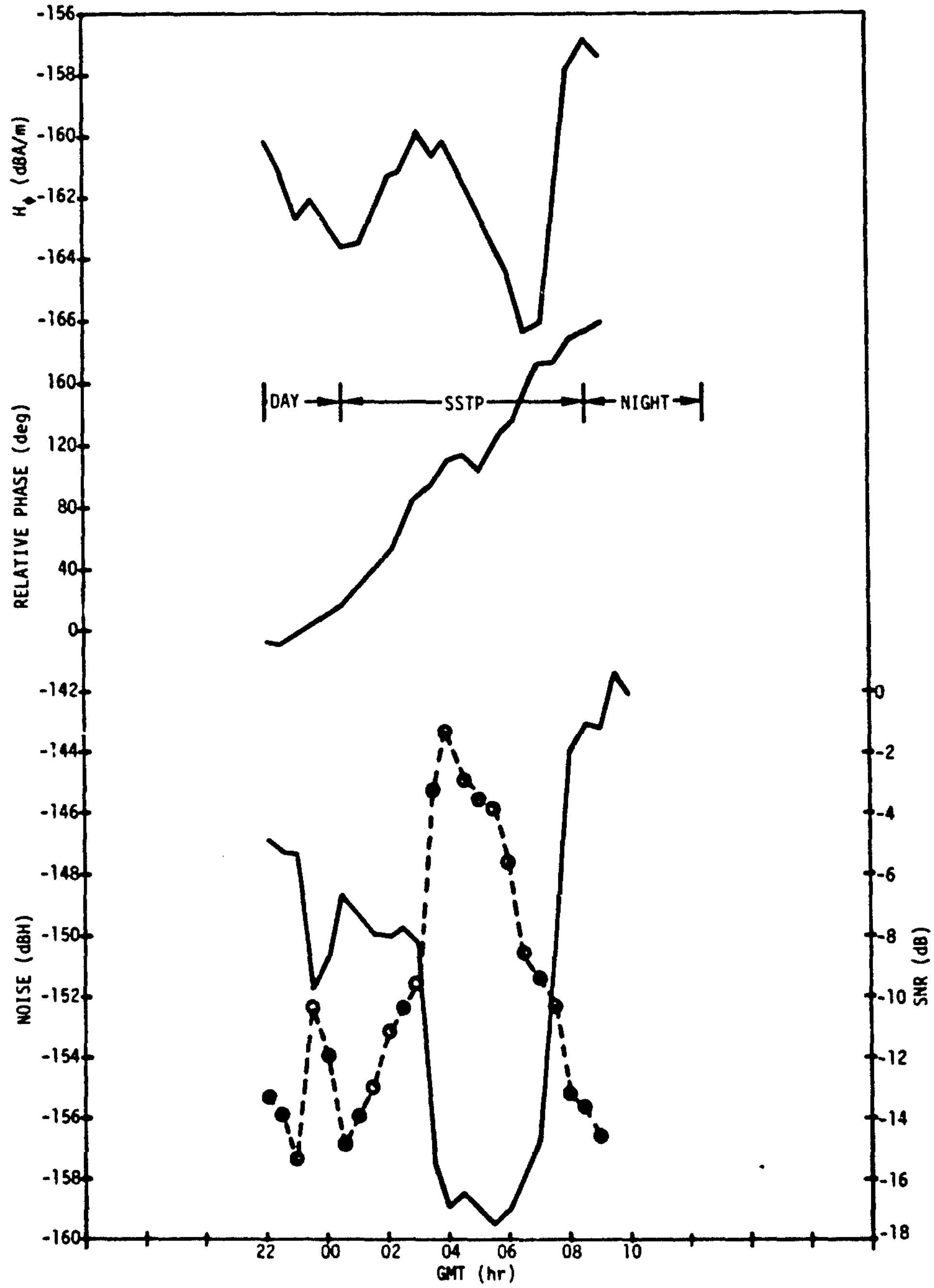

Figure 11. Western-Pacific-Area Data Versus GMT (2200 to 1000 GMT) at 11.5 Mm, 12 October 1977

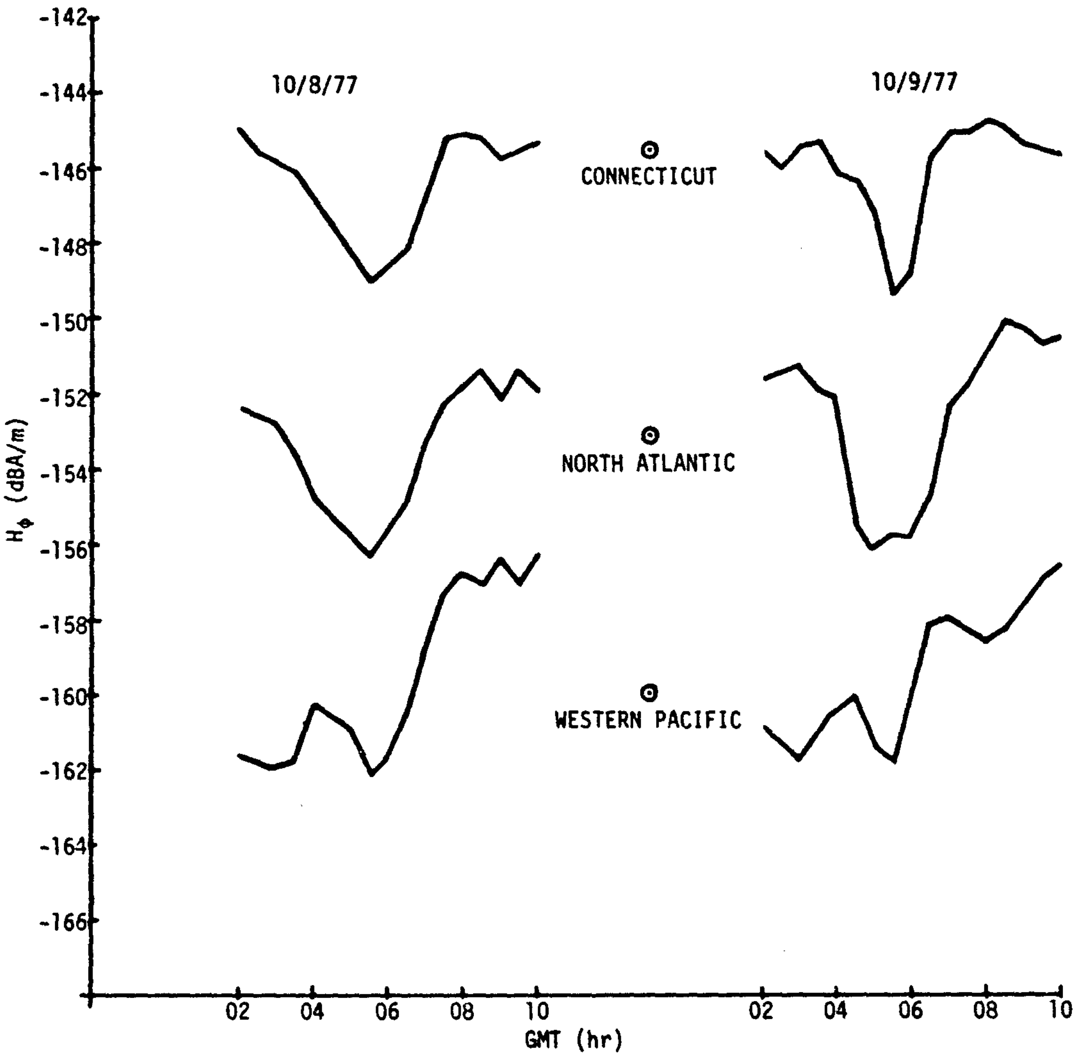

Figure 12. Comparisons of Connecticut, North-Atlantic-Area, and Western-Pacific-Area Field Strengths (0200 to 1000 GMT), 8 and 9 October 1977

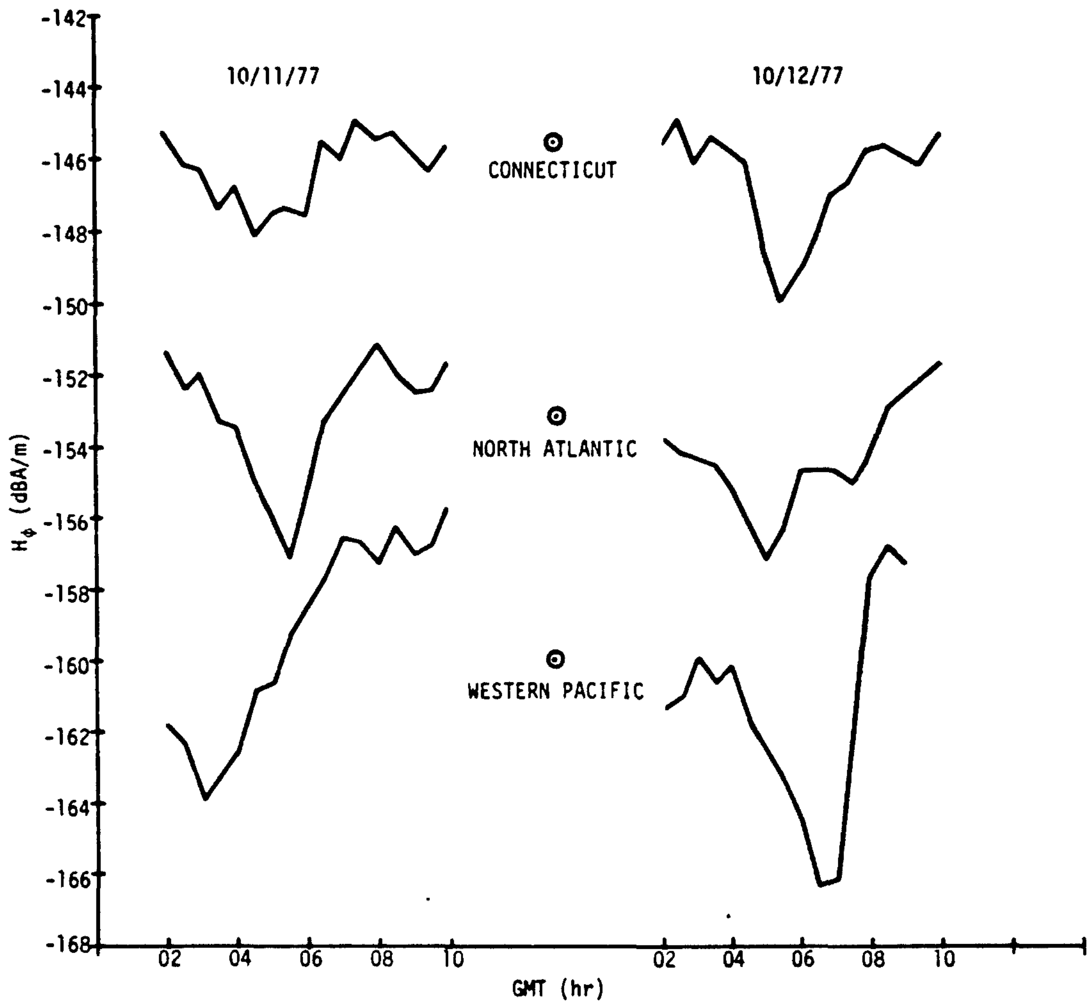

Figure 13. Comparisons of Connecticut, North-Atlantic-Area, and Western-Pacific-Area Field Strengths (0200 to 1000 GMT), 11 and 12 October 1977

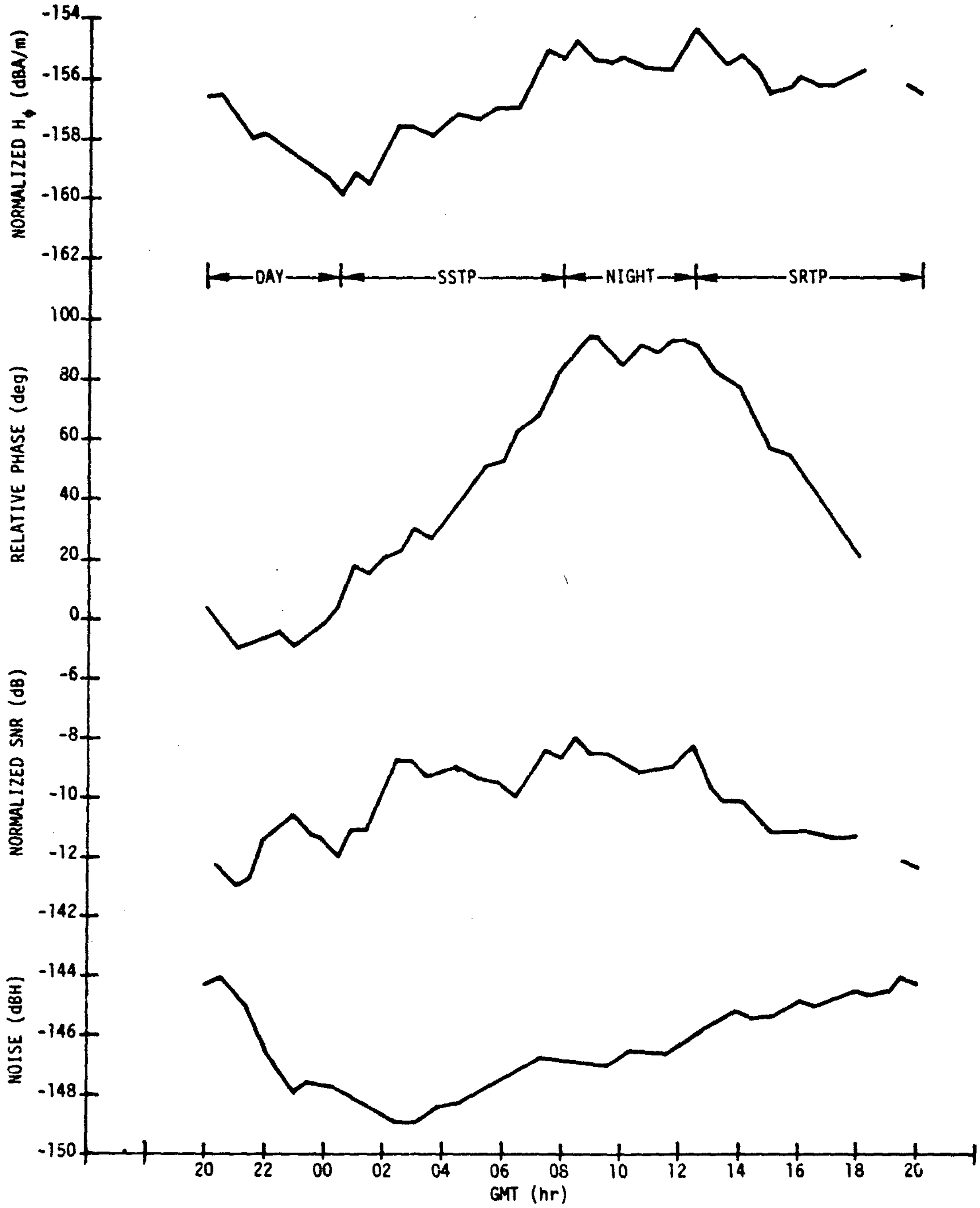

Figure 14. Late-October 1977 Western-Pacific-Area Average Data Versus GMT (ψ = 21 deg)

Appendix A

NORTH-ATLANTIC-AREA SUBMARINE DAILY DATA

The daily 7 to 15 October North-Atlantic-area submarine field-strength (both amplitude and relative phase), effective-noise, and SNR values are plotted versus GMT in figures A-1 through A-9. The WTF antenna phasing angle (ψ) was 291 deg and the transmitting frequency was 76 ±4 Hz.

Amplitude peak-to-trough variations of ~6.5 dB occurred during 4 of the 6 days (8, 9, 11, and 12 October) where there were measurements taken throughout most of the nighttime measurement period (see figures A-2, A-3, A-5, and A-6). The minimum nighttime field strength was measured from 0400 to 0600 during each of these 4 days.

During 7 of 8 days, the average measured $\Delta\phi$ variation was remarkably stable (60.5 ±4 deg), while on 8 October the $\Delta\phi$ variation was only 37 deg (see figure A-2).

The largest daily peak-to-trough variations in the effective noise (12 to 14 dB) were measured during 11 and 13 October (figures A-5 and A-7), each being one day later than the largest daily peak-to-trough variations measured in the Western Pacific.

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.

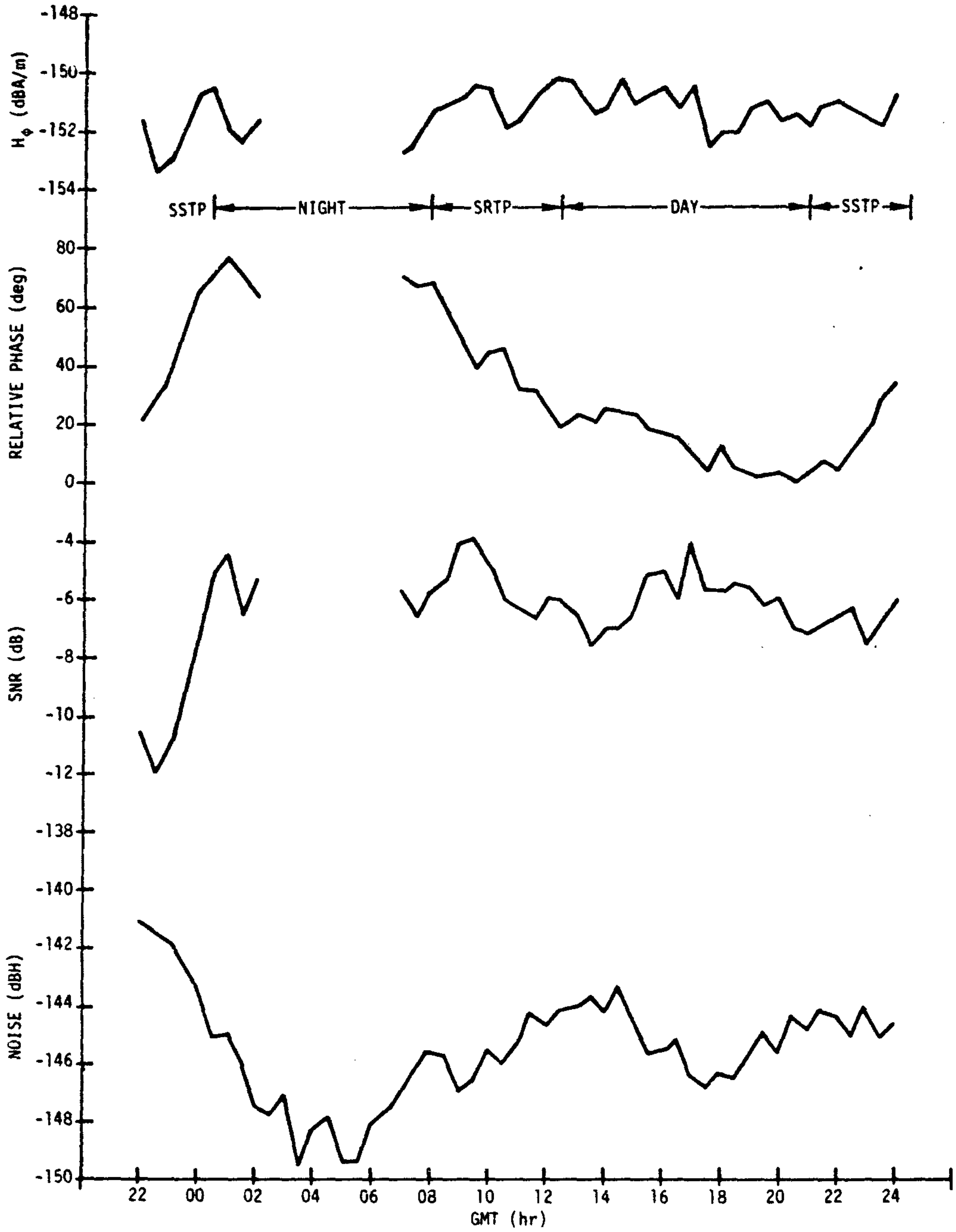

Figure A-1. North-Atlantic-Area Submarine Data Versus GMT (ψ = 291 deg), 7 October 1977

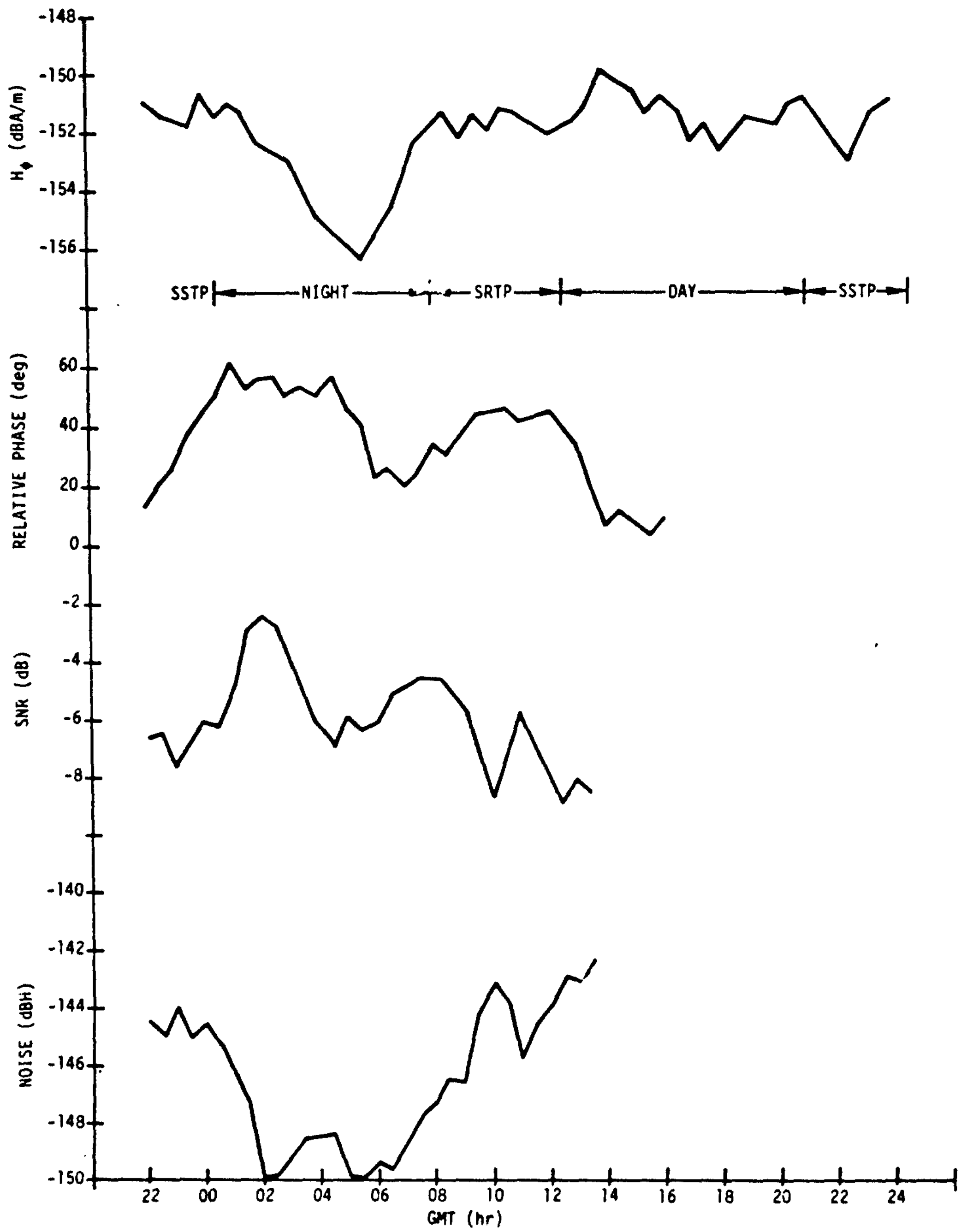

Figure A-2. North-Atlantic-Area Submarine Data Versus GMT (ψ = 291 deg), 8 October 1977

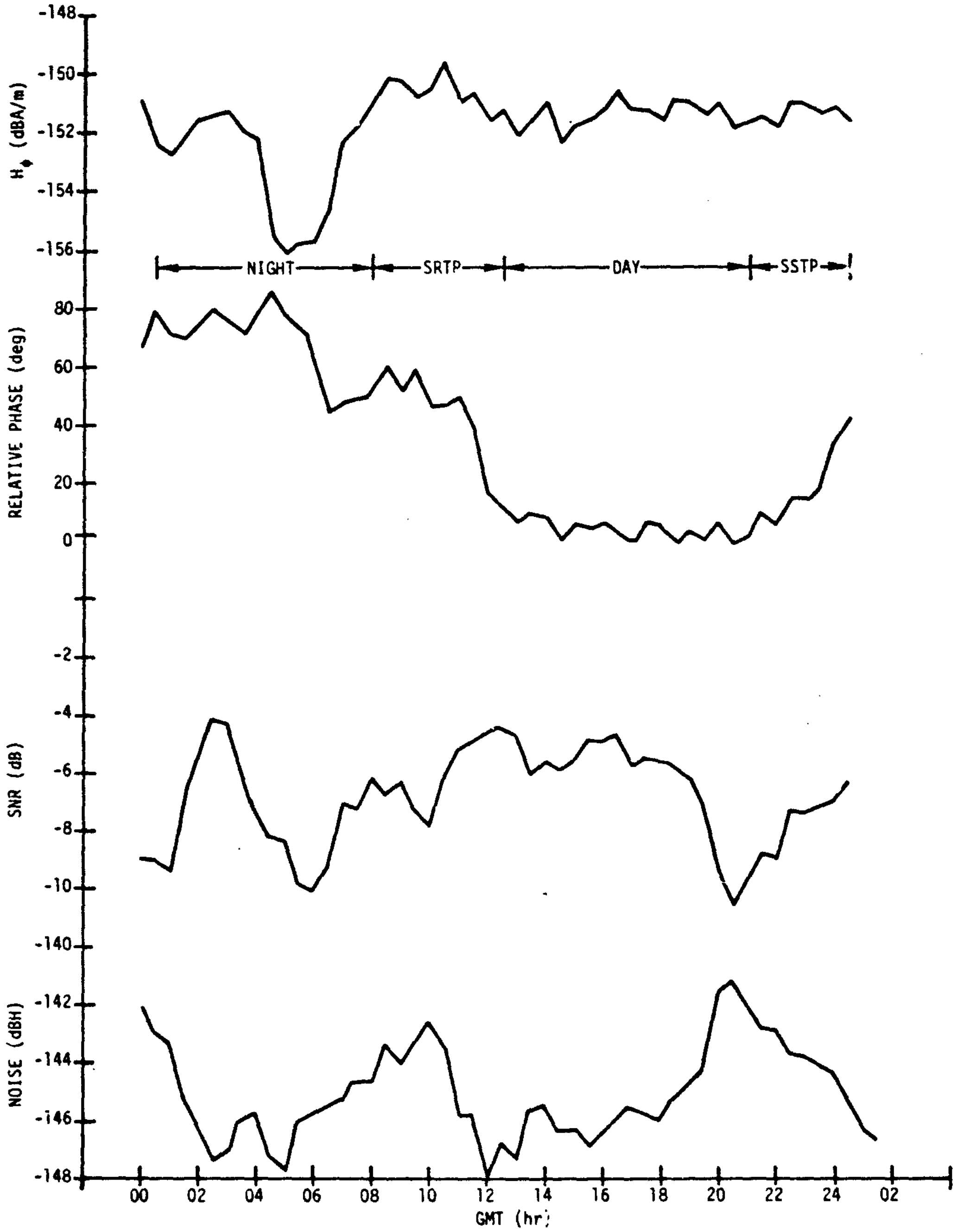

Figure A-3. North-Atlantic-Area Submarine Data Versus GMT (ψ = 291 deg), 9 October 1977

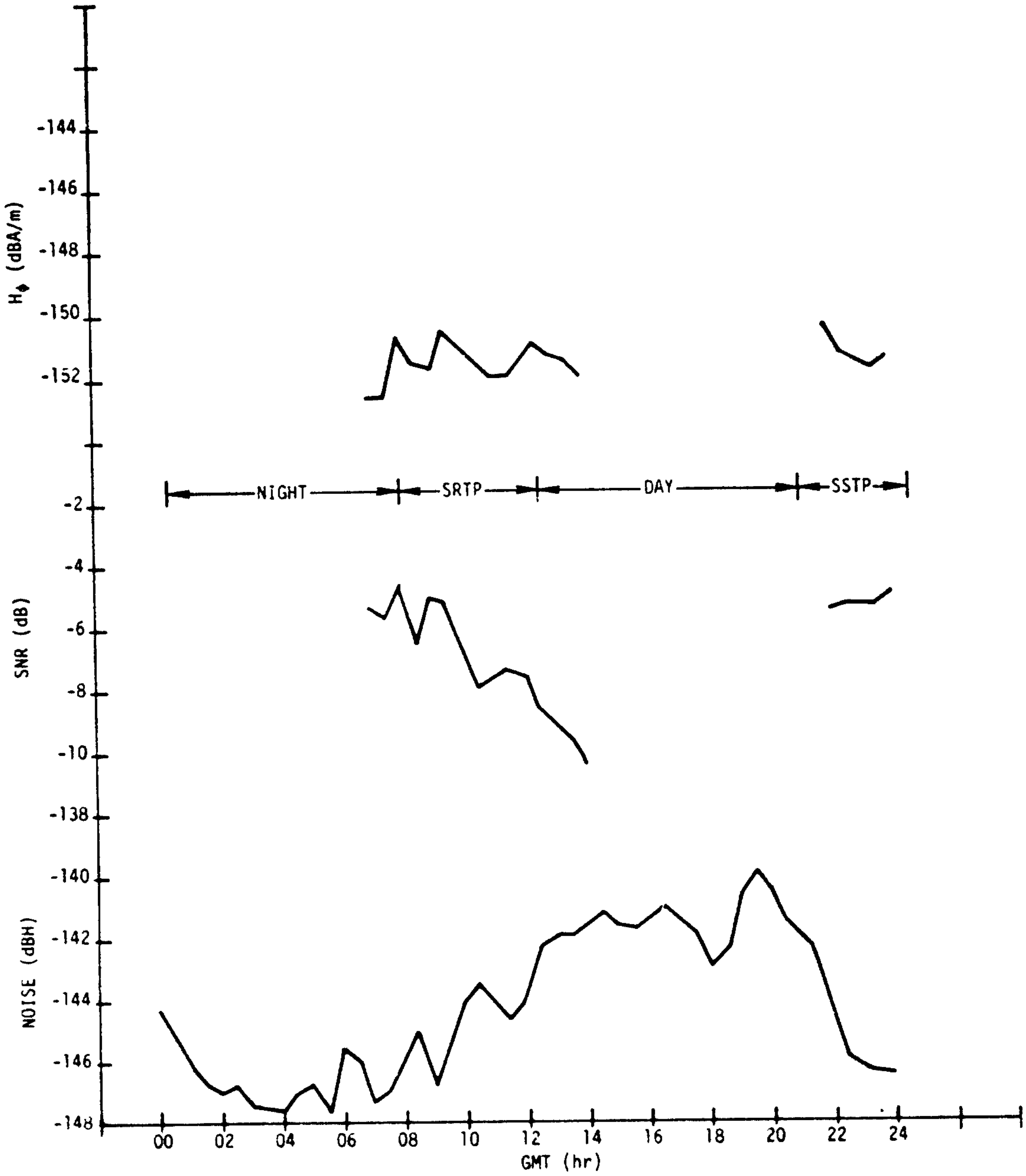

Figure A-4. North-Atlantic-Area Submarine Data Versus GMT (ψ = 291 deg), 10 October 1977

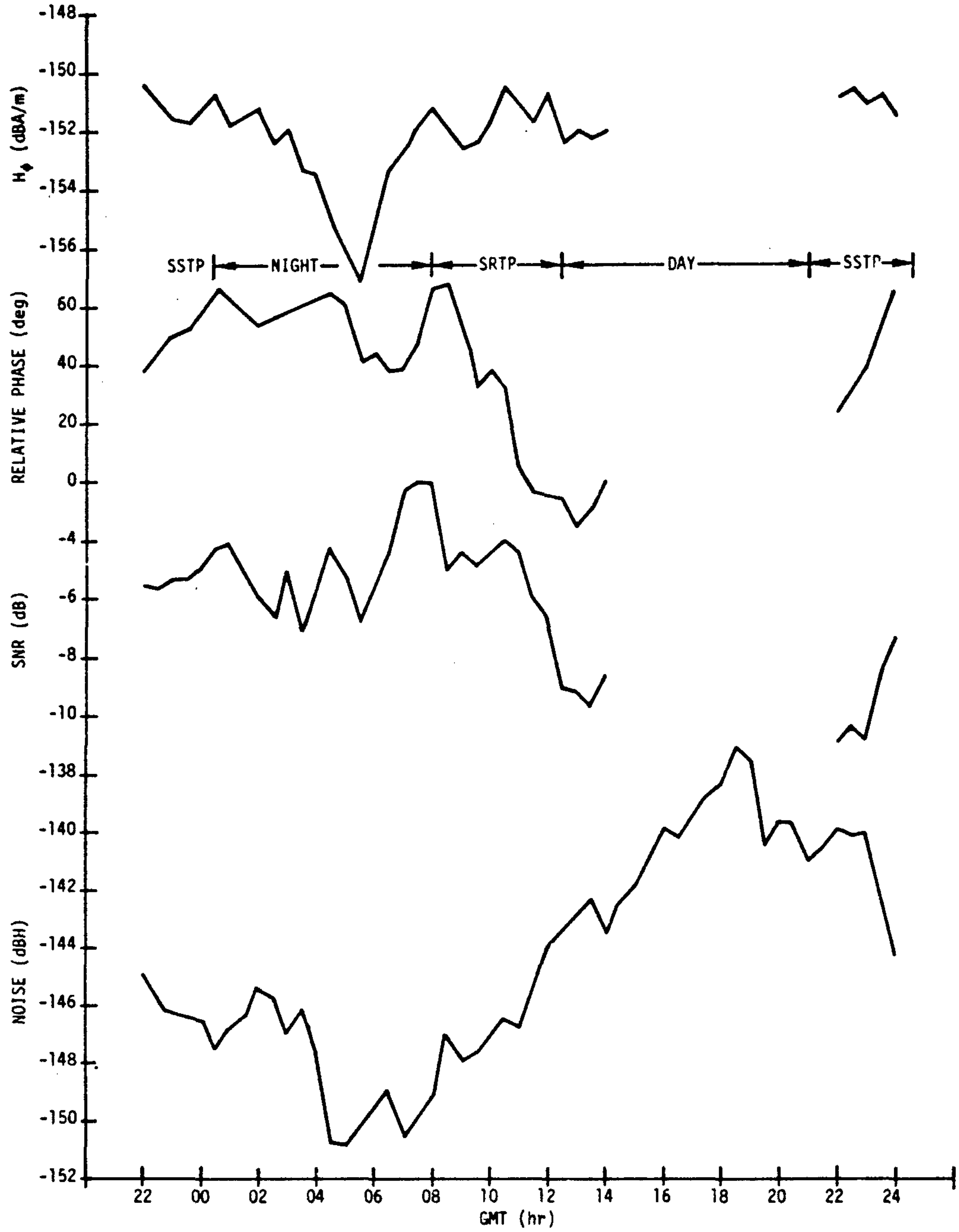

Figure A-5. North-Atlantic-Area Submarine Data Versus GMT (ψ = 291 deg), 11 October 1977

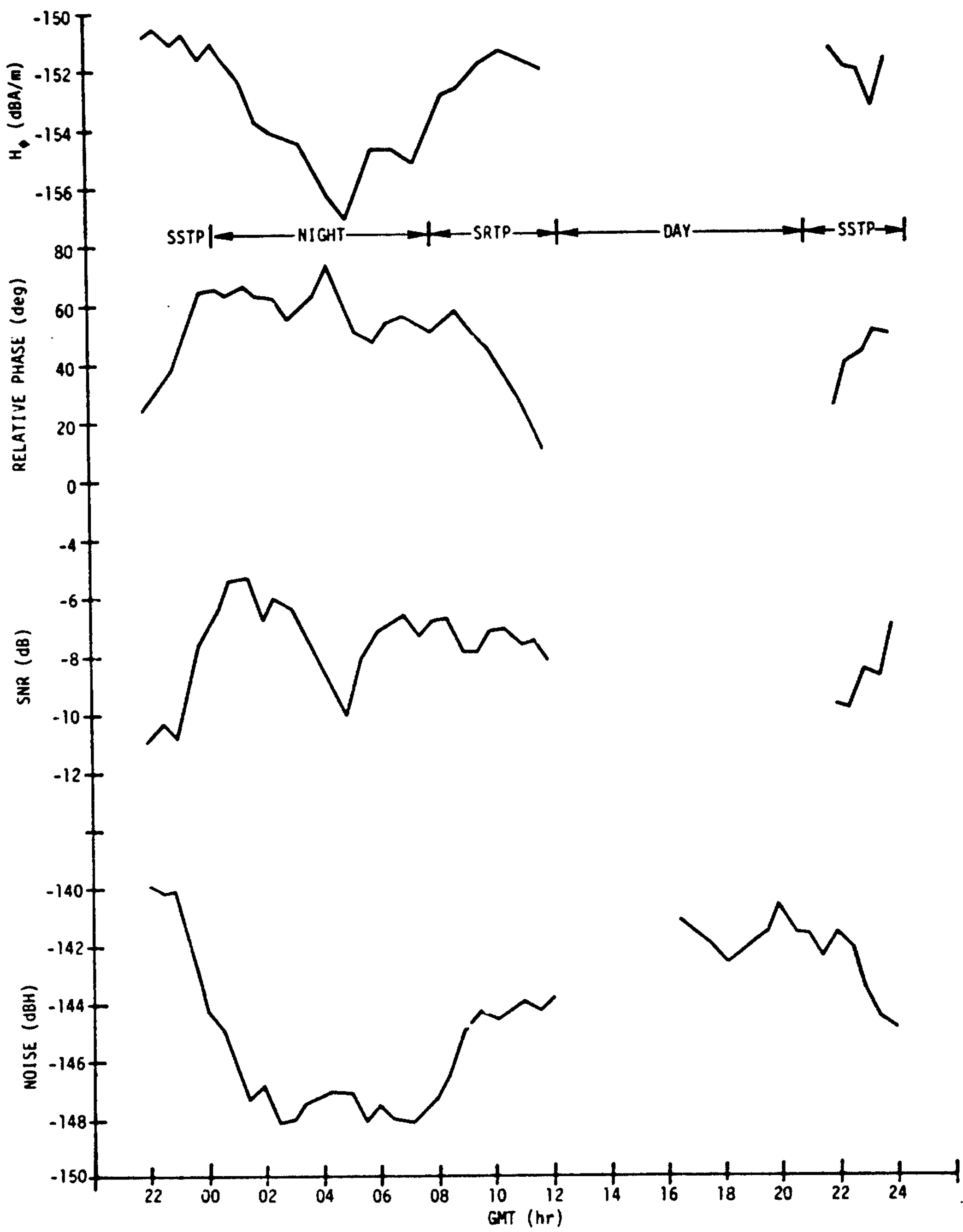

Figure A-6. North-Atlantic-Area Submarine Data Versus GMT (ψ = 291 deg), 12 October 1977

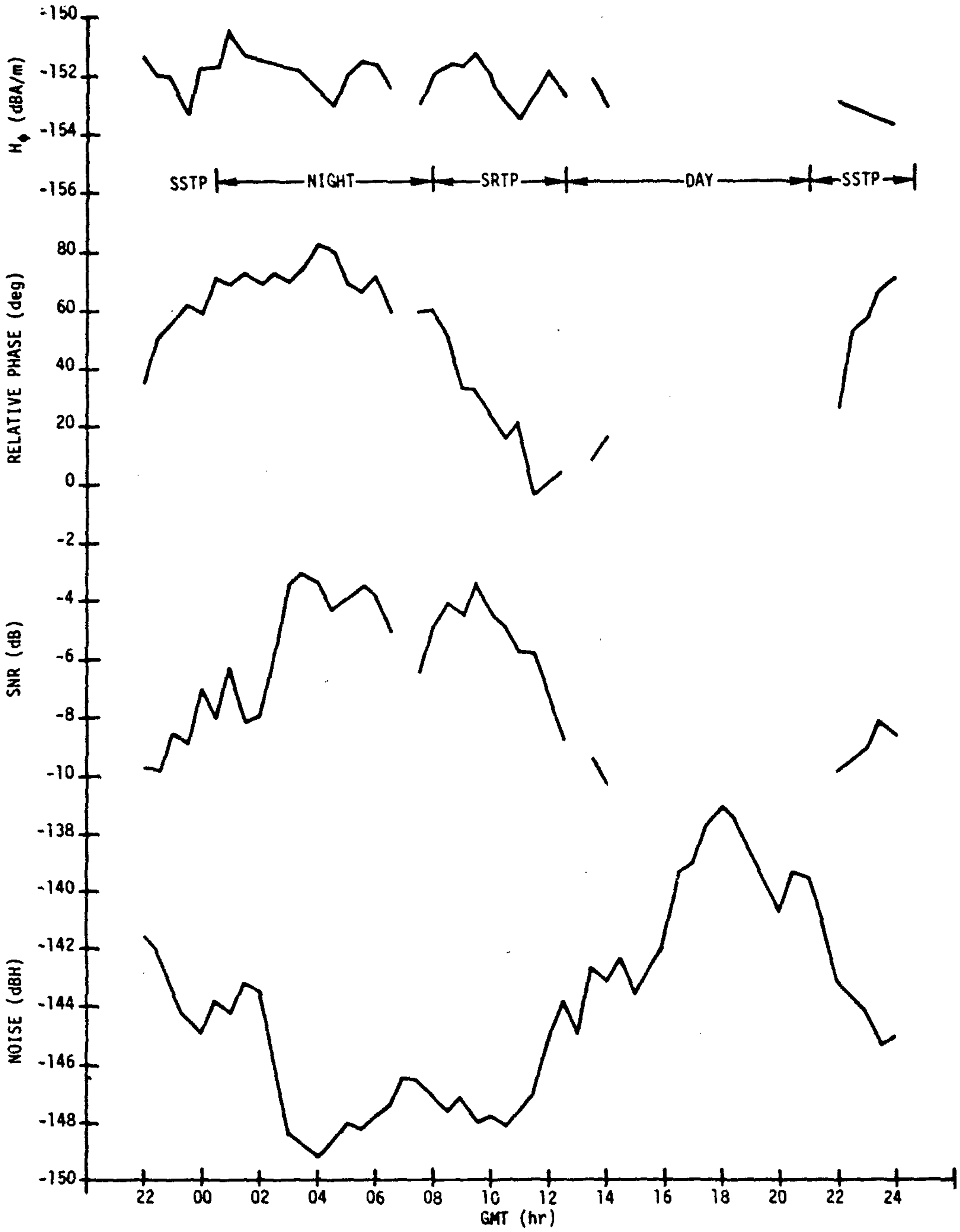

Figure A-7. North-Atlantic-Area Submarine Data Versus GMT (ψ = 291 deg), 13 October 1977

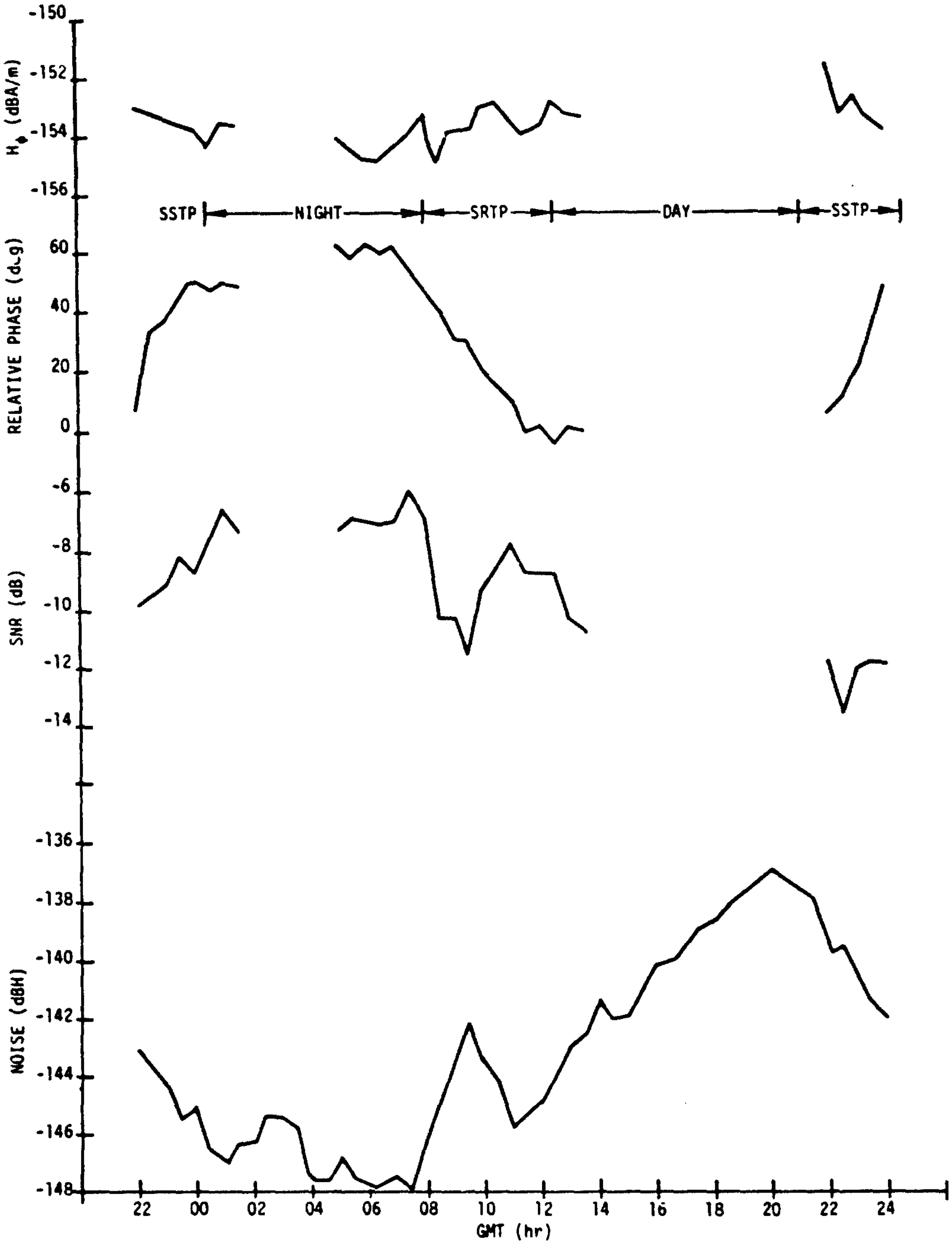

Figure A-8. North-Atlantic-Area Submarine Data Versus GMT (ψ = 291 deg), 14 October 1977

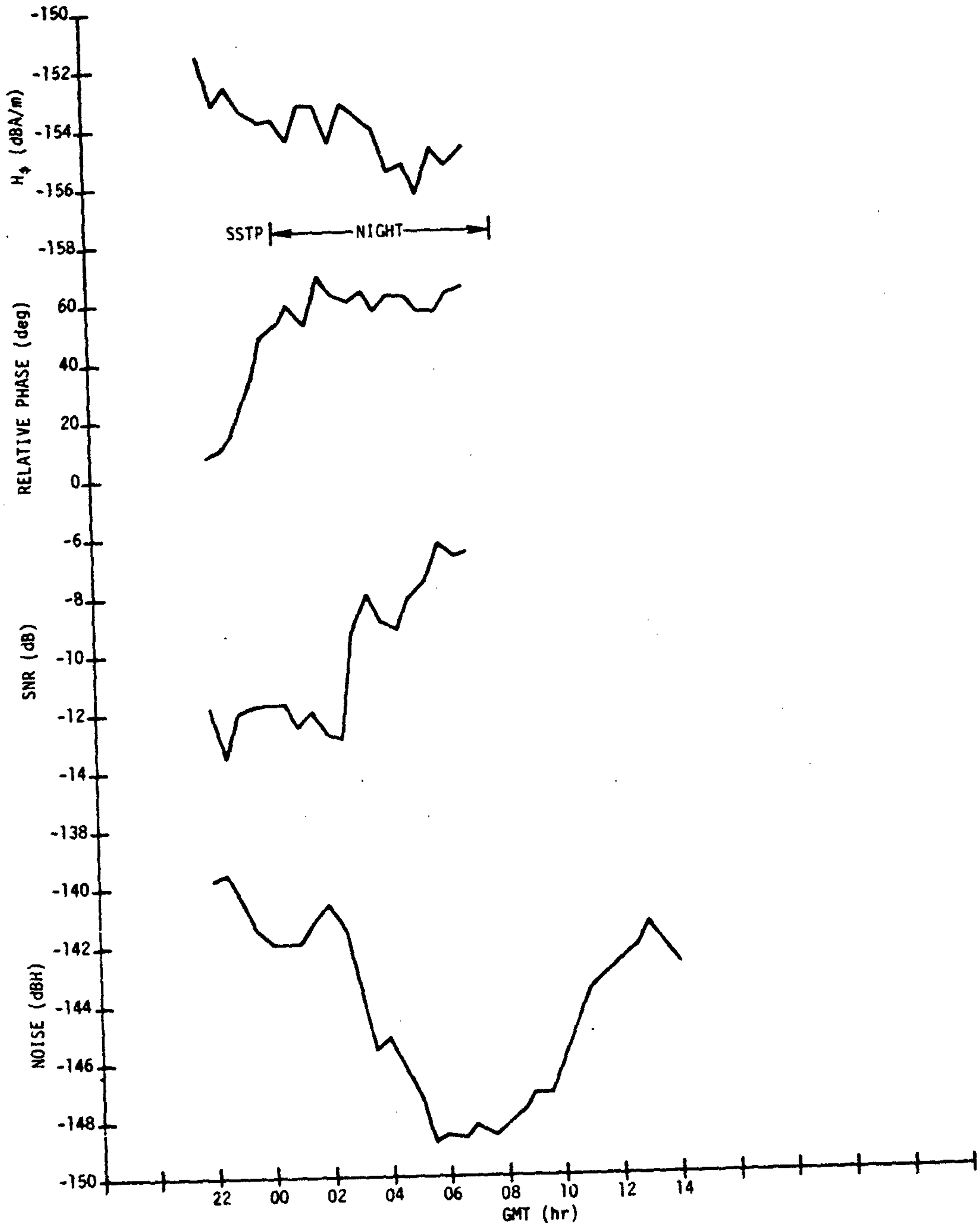

Figure A-9. North-Atlantic-Area Submarine Data Versus GMT (ψ = 291 deg), 15 October 1977

Appendix B

OCTOBER 1977 CONNECTICUT DAILY DATA

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

As we mentioned previously,[5] the Connecticut effective-noise measurements are sometimes contaminated by industrial noise. Thus, the effective-noise values presented in this appendix are on the high side.

The October daily field-strength (both amplitude and relative phase), effective-noise, and SNR values are plotted versus GMT in figures B-1 through B-29. The WTF antenna phasing angle (ψ) was 291 deg from 2 through 17 October (and on 31 October) and 21 deg from 18 through 30 October. The transmitting frequency was 76 ±¼ Hz.

Note that, with the exception of the 2 and 3 October data (figures B-1 and B-2), all of the October Connecticut data are plotted in 15-min increments, rather than in 30-min increments. Also, each point is the sample ending time rather than the sample starting time.

For a WTF antenna phasing angle of 291 deg, the average Connecticut field strength should equal ~-143.3 dBA/m during the day and ~-145.5 dBA/m at night. For a WTF antenna phasing angle of 21 deg, the Connecticut field strengths should be ~0.8 dB lower. Referring to figures B-1 through B-23, we see that, with the exception of the nighttime minimum field-strength period, the field-strength levels are about as expected.

The late-October measurement period is highlighted by the "Halloween effect." This effect has been observed for the past seven consecutive years (1970 to 1976) during the period 27 October to 1 November.[10,11] It is marked by an average drop in ELF nighttime field strengths of 2 to 6 dB relative to the preceding or following nights.

Since the 26 to 28 October 1977 period was characterized by the most magnetic-storm activity during October, we expected that the "Halloween effect" would be substantial. However, this year the effect reversed itself. During 26, 28, 29, and 30 October (figures B-24, B-26, B-27, and B-28), the average nighttime field strength was 1 to 1.5 dB higher than normal.

During 27 October (figure B-25), the average nighttime field strength was about as expected except for a 2 dB dip around 1000 GMT. A decrease was also observed at the same time in the Western Pacific (appendix C). The largest nighttime field-strength increase observed in the Western Pacific occurred on 29 October, where the 1000 to 1200 GMT nighttime field strength was 3 to 4 dB higher than that measured during 26, 27, and 28 October.

Amplitude peak-to-trough variations of 5 dB or greater occurred during 7 of the first 11 October measurement days (2, 3, 4, 8, 9, 10, and 12 October). The largest variation (~9 dB) occurred on 12 October (figure B-11).

However, from 13 October until the end of November, there were zero days (out of 47) where the amplitude peak-to-trough variation was 5 dB or greater.

The October night-to-day relative-phase variation was 20.5 ±5 deg, which corresponds to a monthly average Δ(c/v) of 0.14. The largest relative-phase variation (28 deg) occurred on 19 October (figure B-17), while the smallest relative-phase variation (12 deg) occurred on 4 October (figure B-3).

The largest daily peak-to-trough variation in effective noise (~14 dB) was also measured on 19 October (figure B-17).

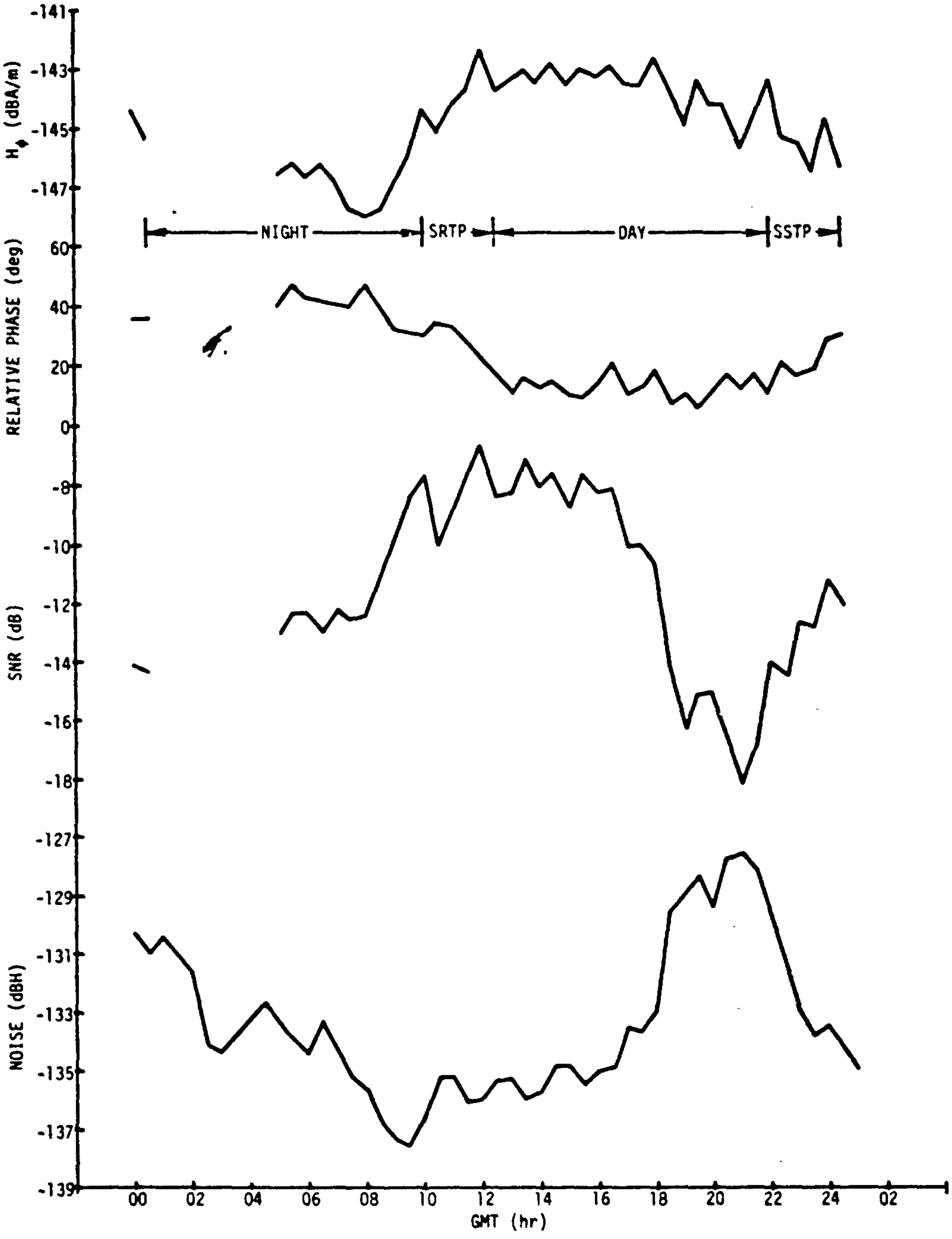

Figure B-1. Connecticut Data Versus GMT
(ψ = 291 deg), 2 October 1977

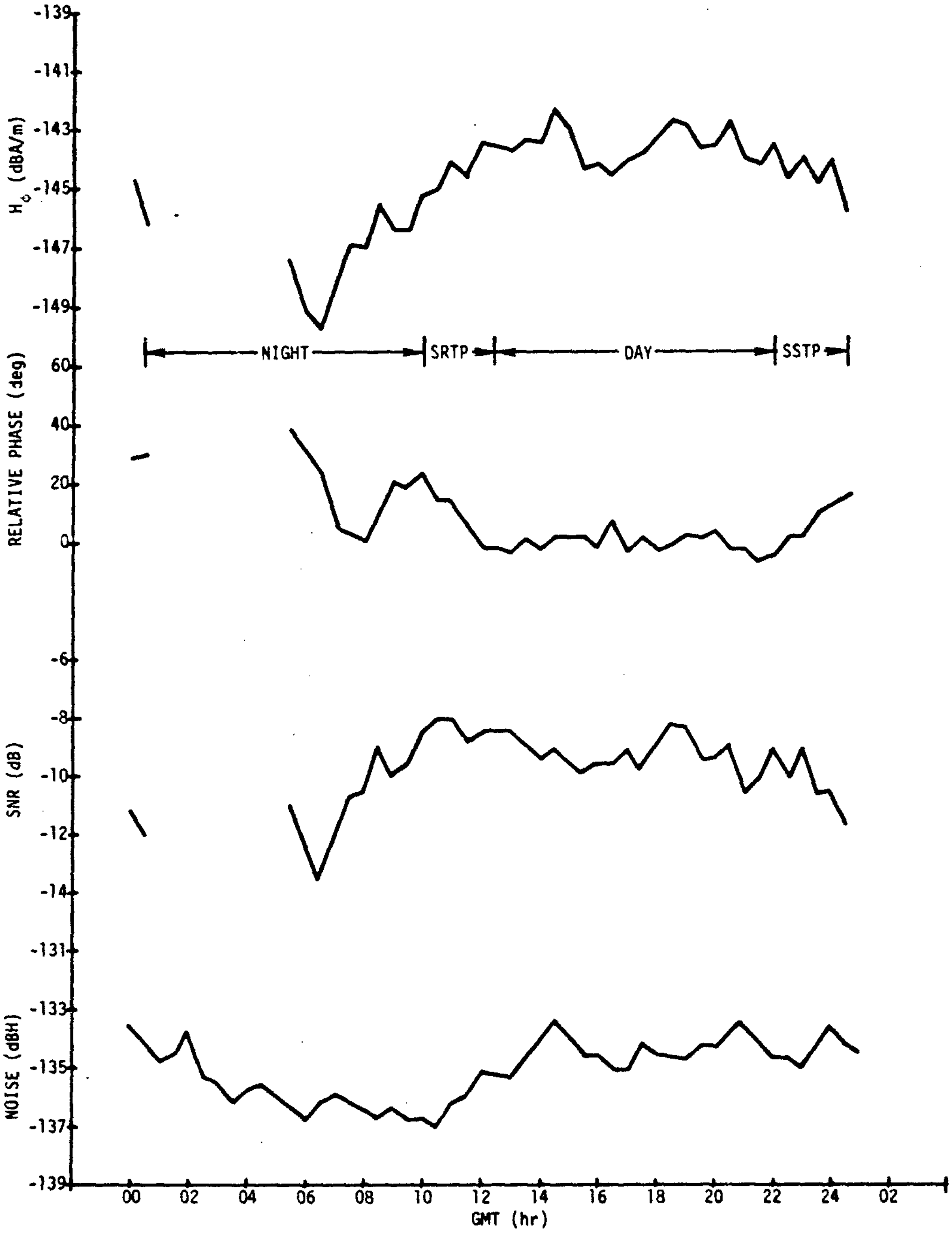

Figure B-2. Connecticut Data Versus GMT
(ψ = 291 deg), 3 October 1977

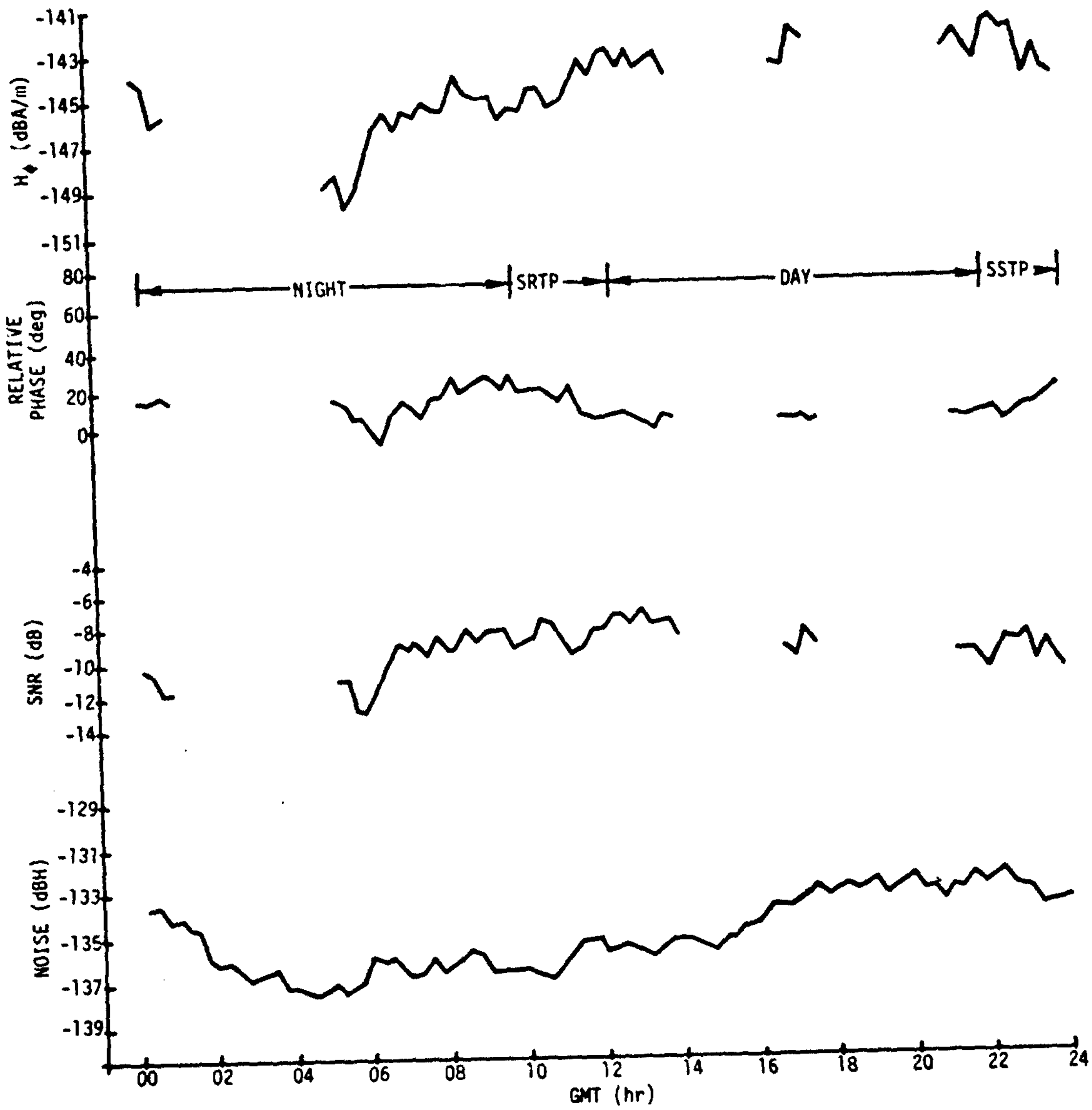

Figure B-3. Connecticut Data Versus GMT
(ψ = 291 deg), 4 October 1977

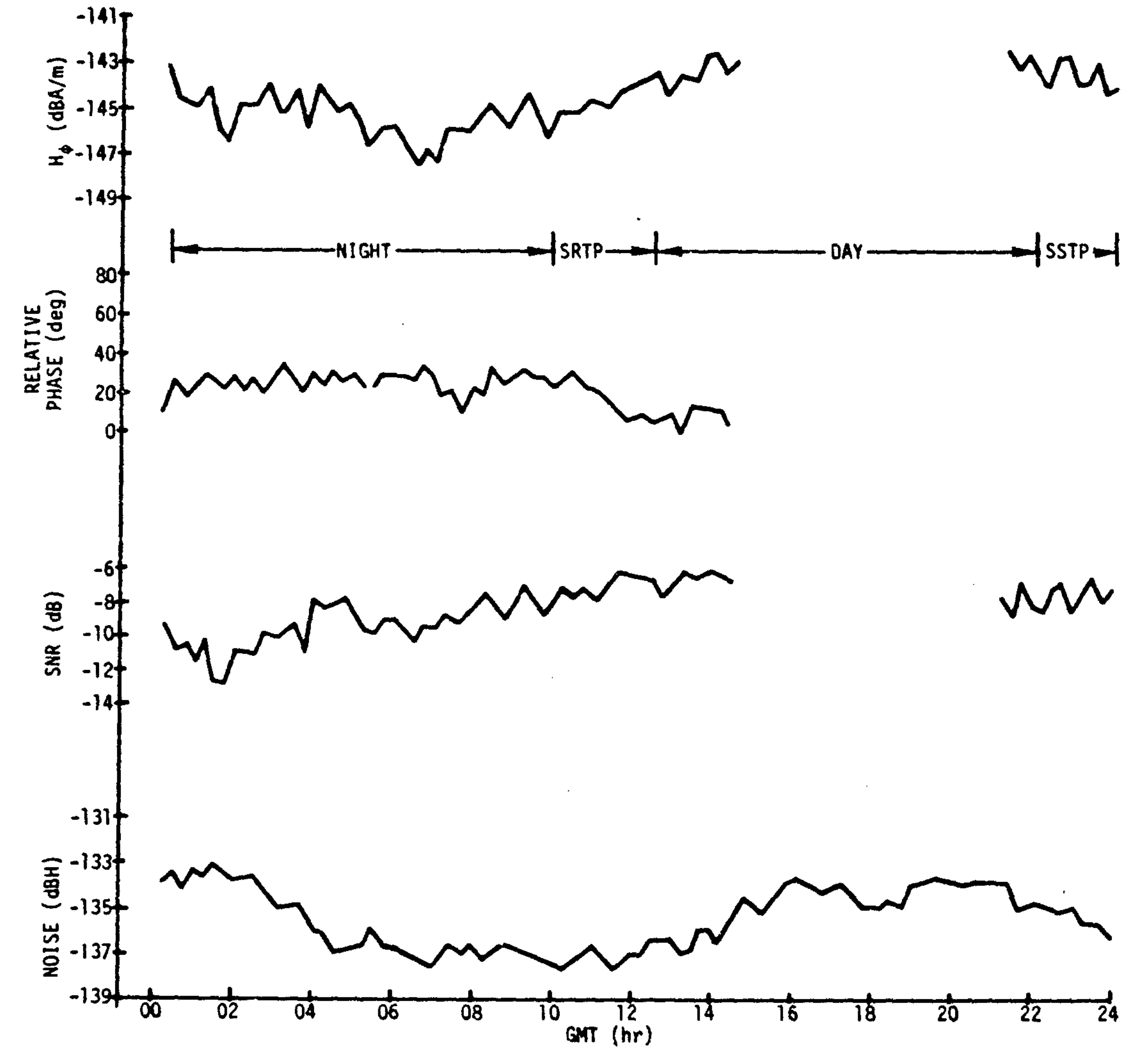

Figure B-4. Connecticut Data Versus GMT
(ϕ = 291 deg), 5 October 1977

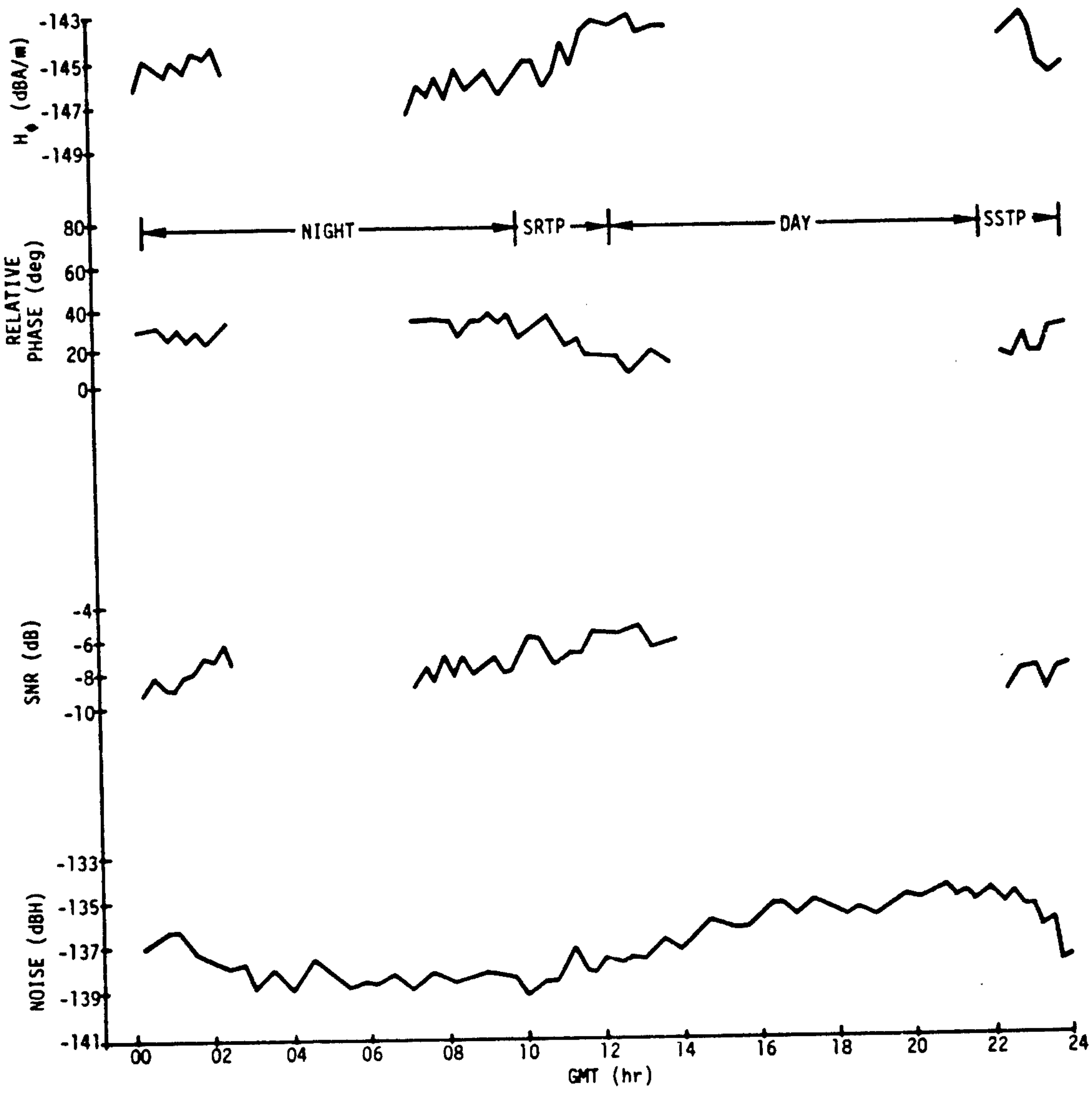

Figure B-5. Connecticut Data Versus GMT (ψ = 291 deg), 6 October 1977

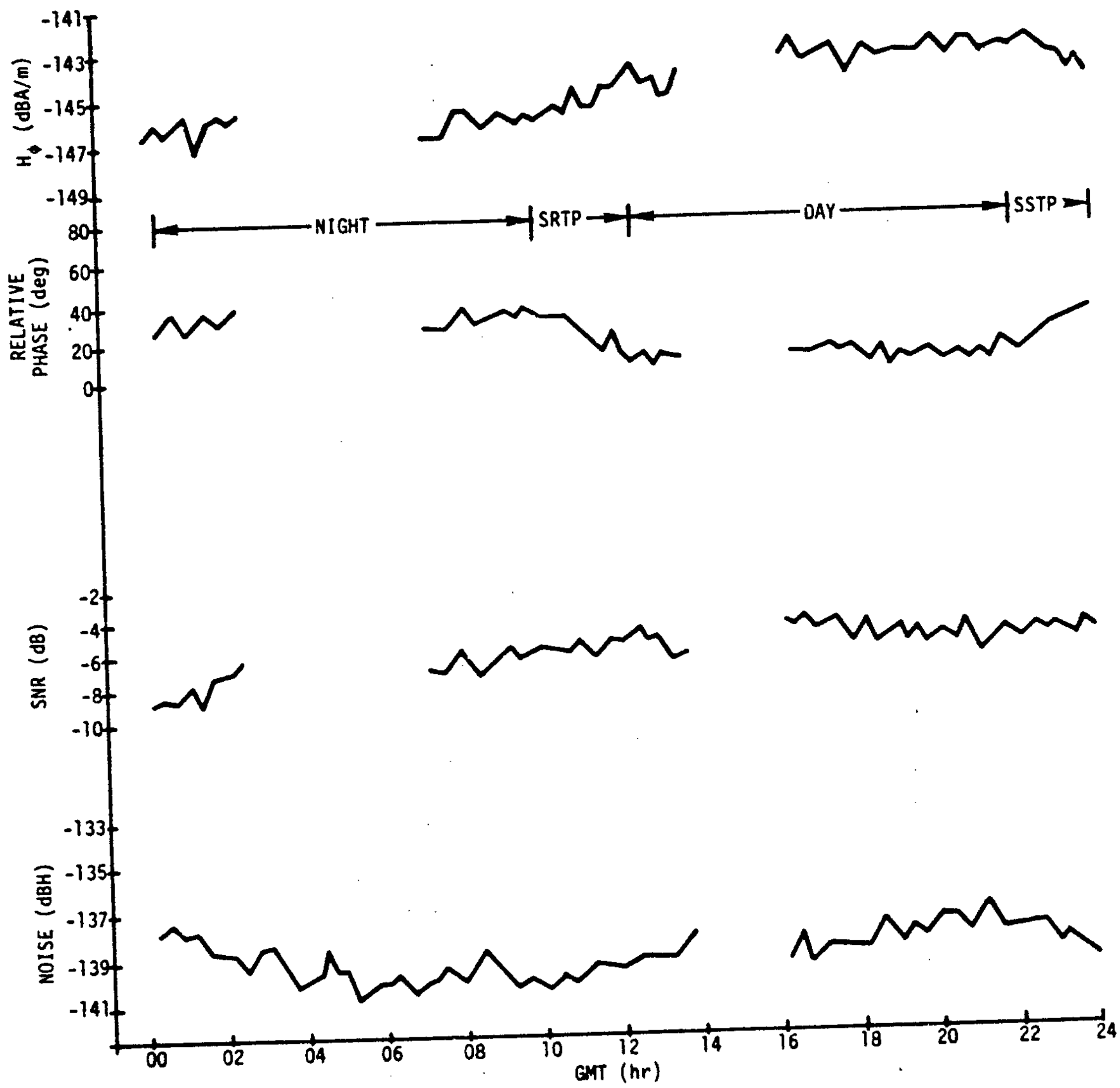

Figure B-6. Connecticut Data Versus GMT (ψ = 291 deg), 7 October 1977

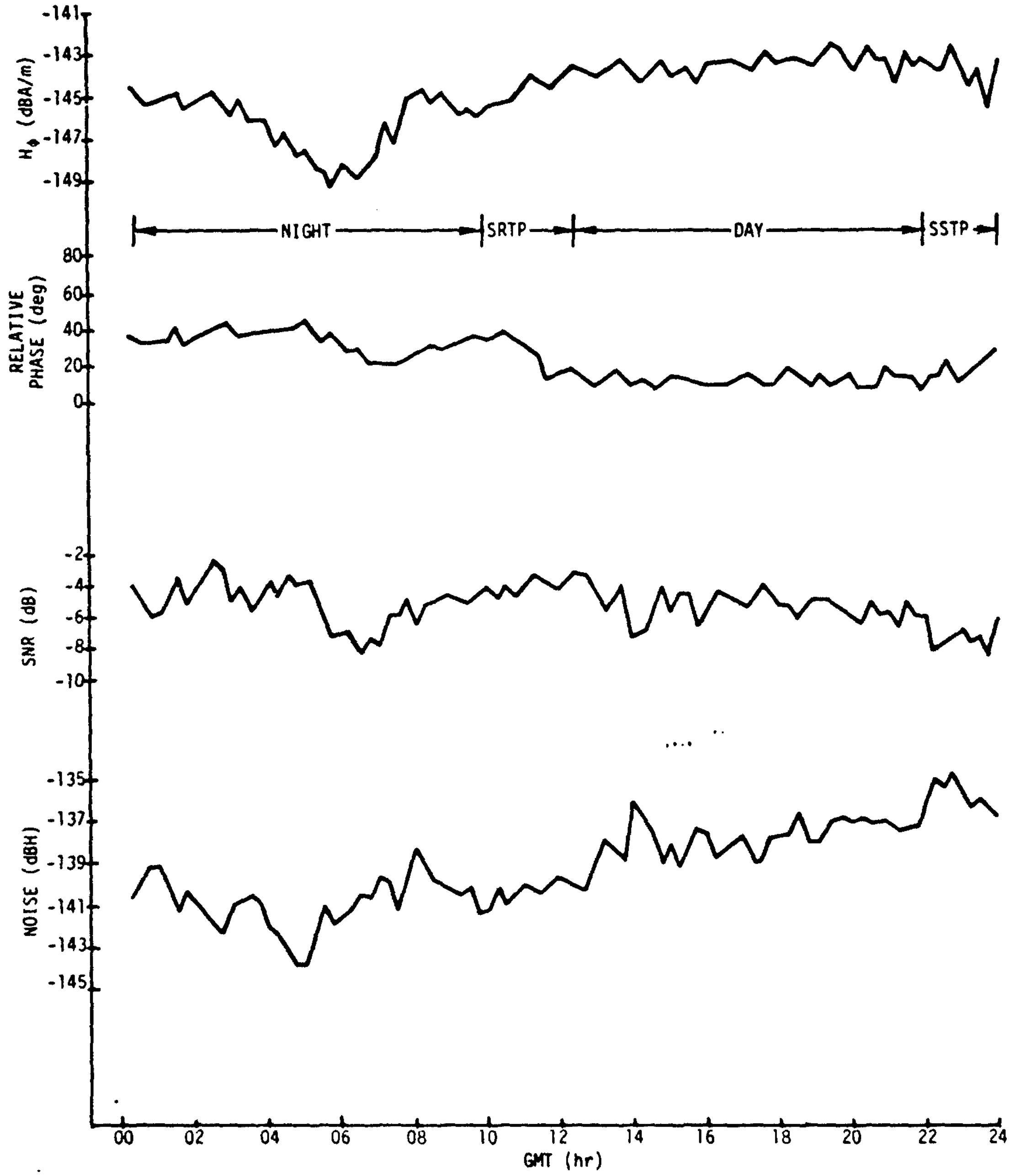

Figure B-7. Connecticut Data Versus GMT (ψ = 291 deg), 8 October 1977

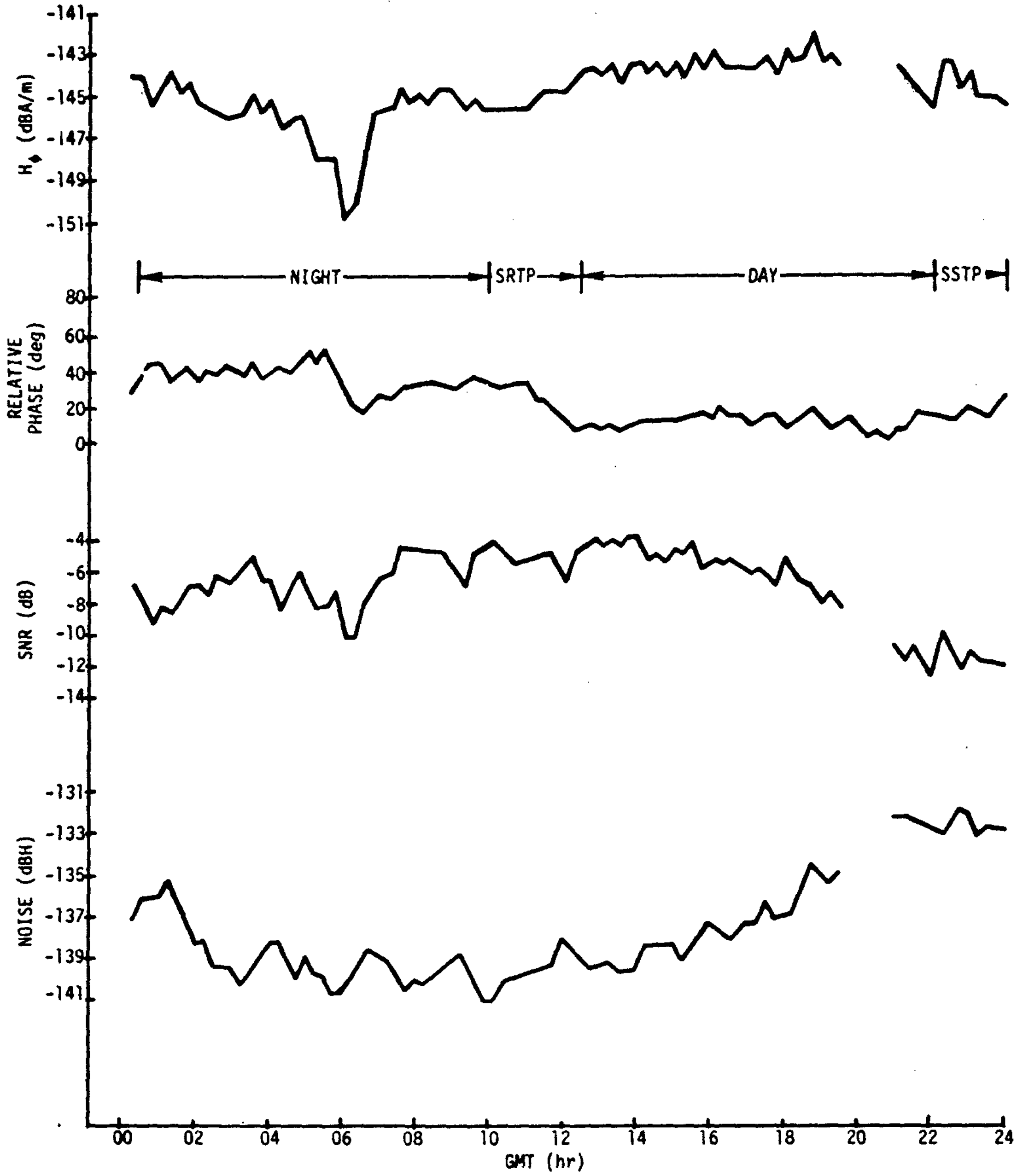

Figure B-8. Connecticut Data Versus GMT
(ψ = 291 deg), 9 October 1977

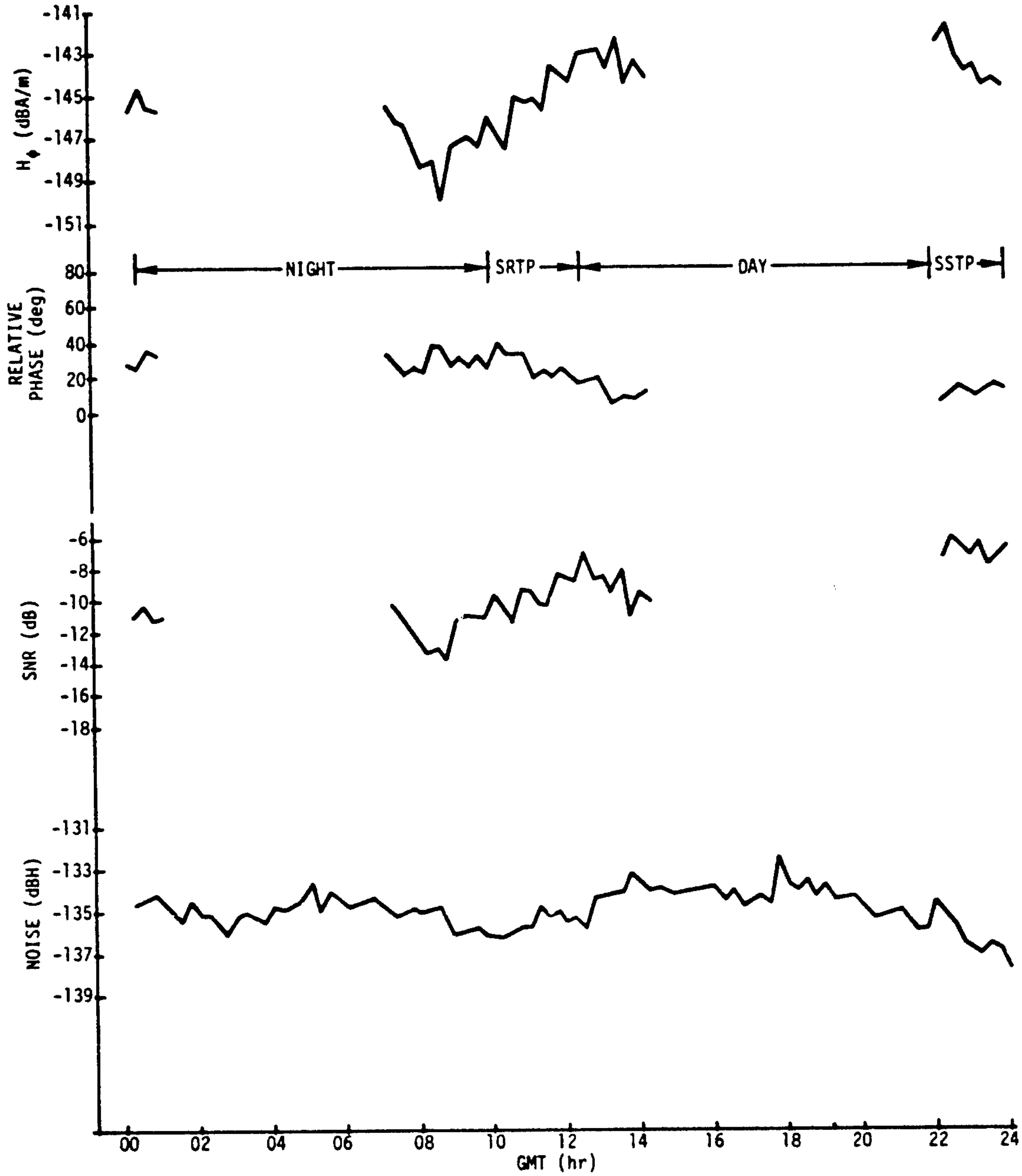

Figure B-9. Connecticut Data Versus GMT
(ψ = 291 deg), 10 October 1977

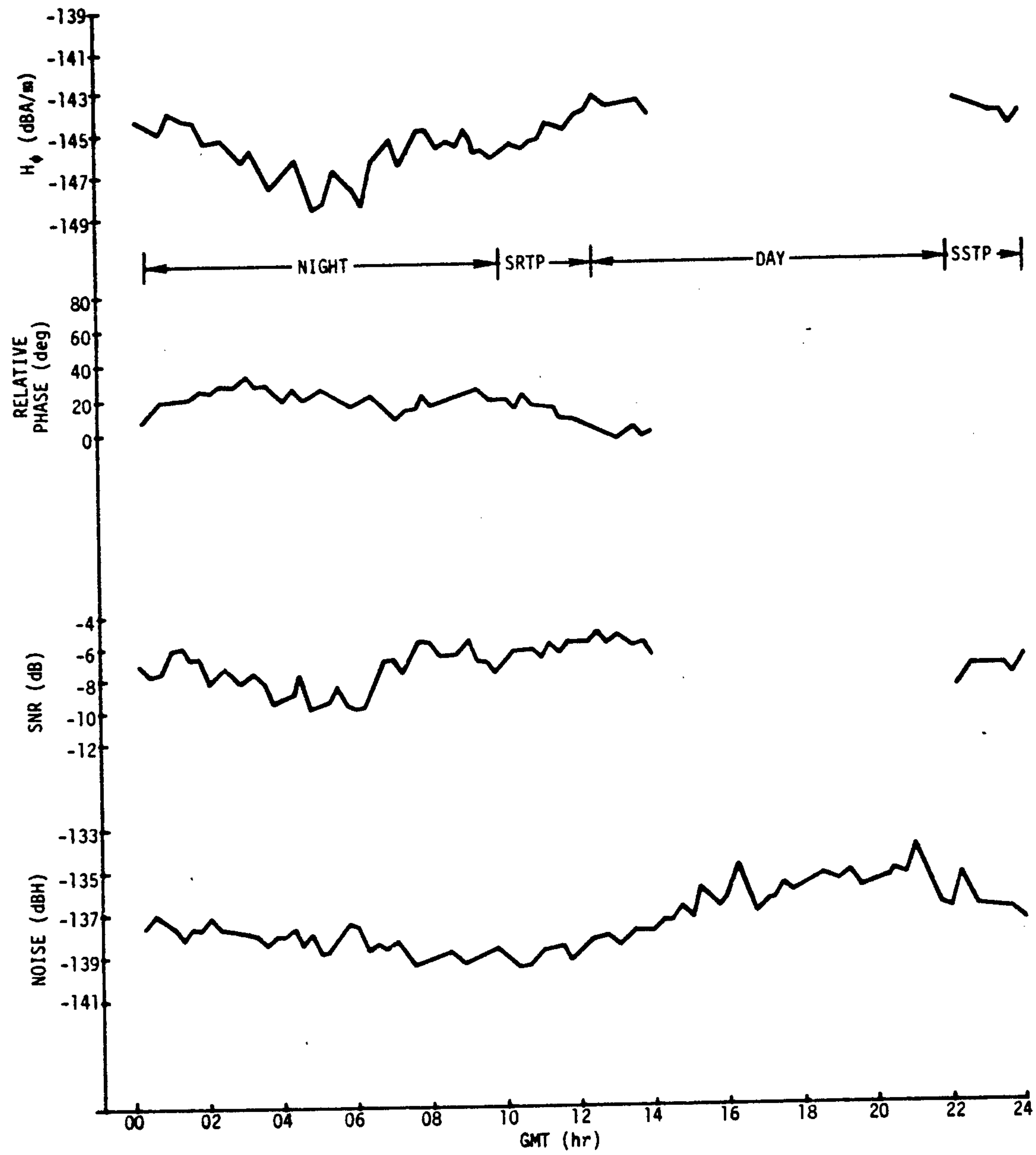

Figure B-10. Connecticut Data Versus GMT (ψ = 291 deg), 11 October 1977

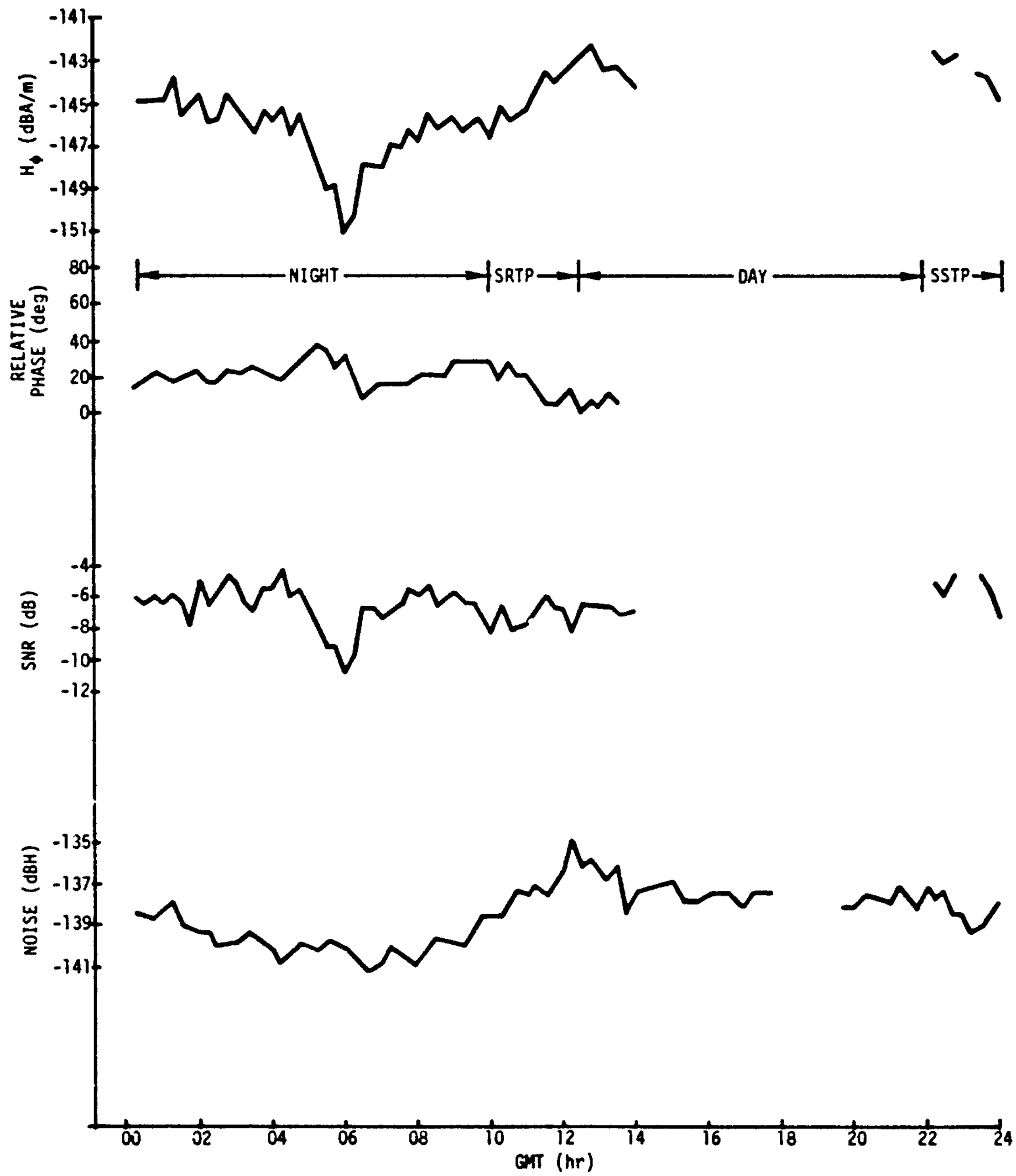

Figure B-11. Connecticut Data Versus GMT
(ψ = 291 deg), 12 October 1977

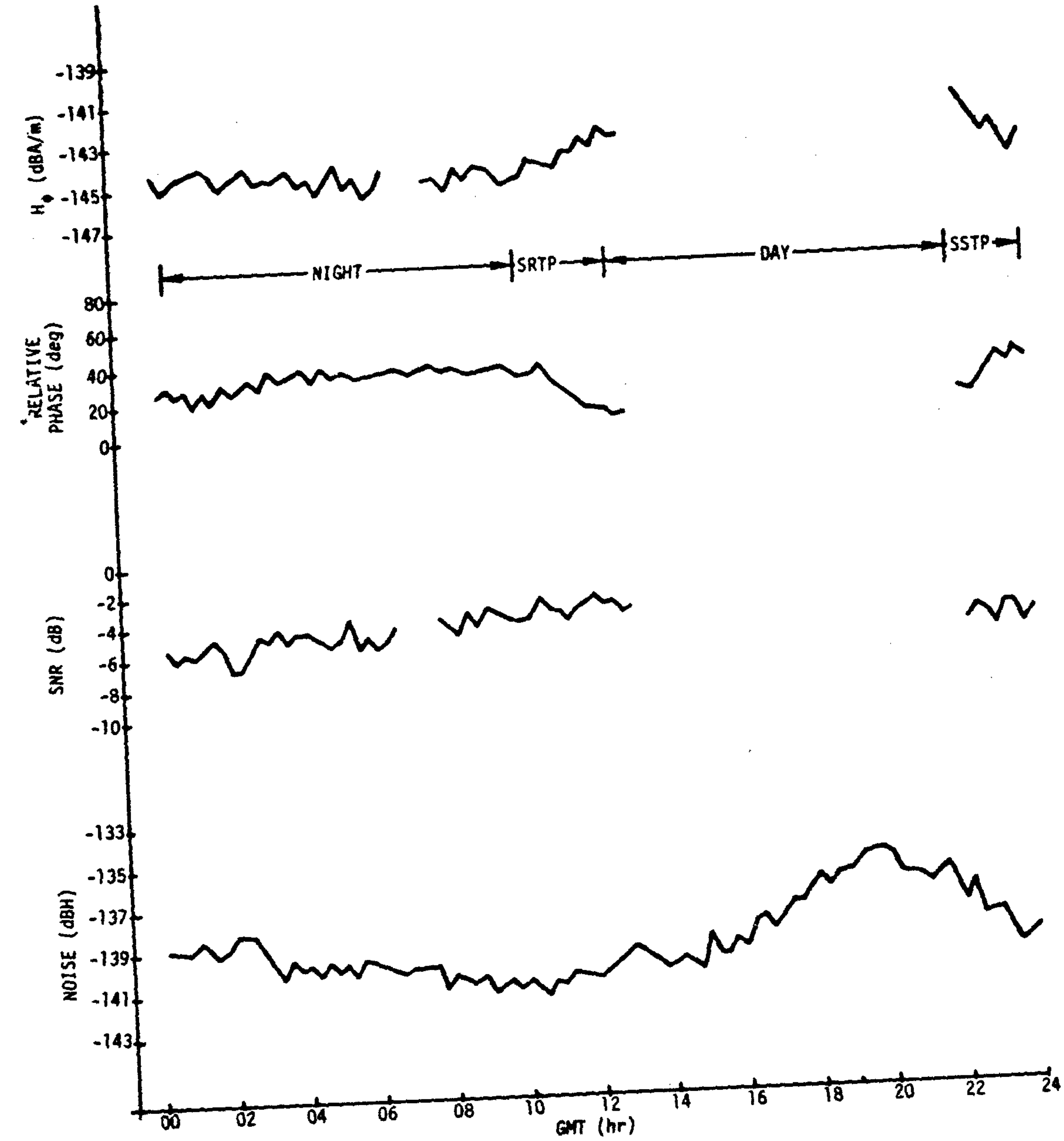

Figure B-12. Connecticut Data Versus GMT
(ϕ = 291 deg), 13 October 1977

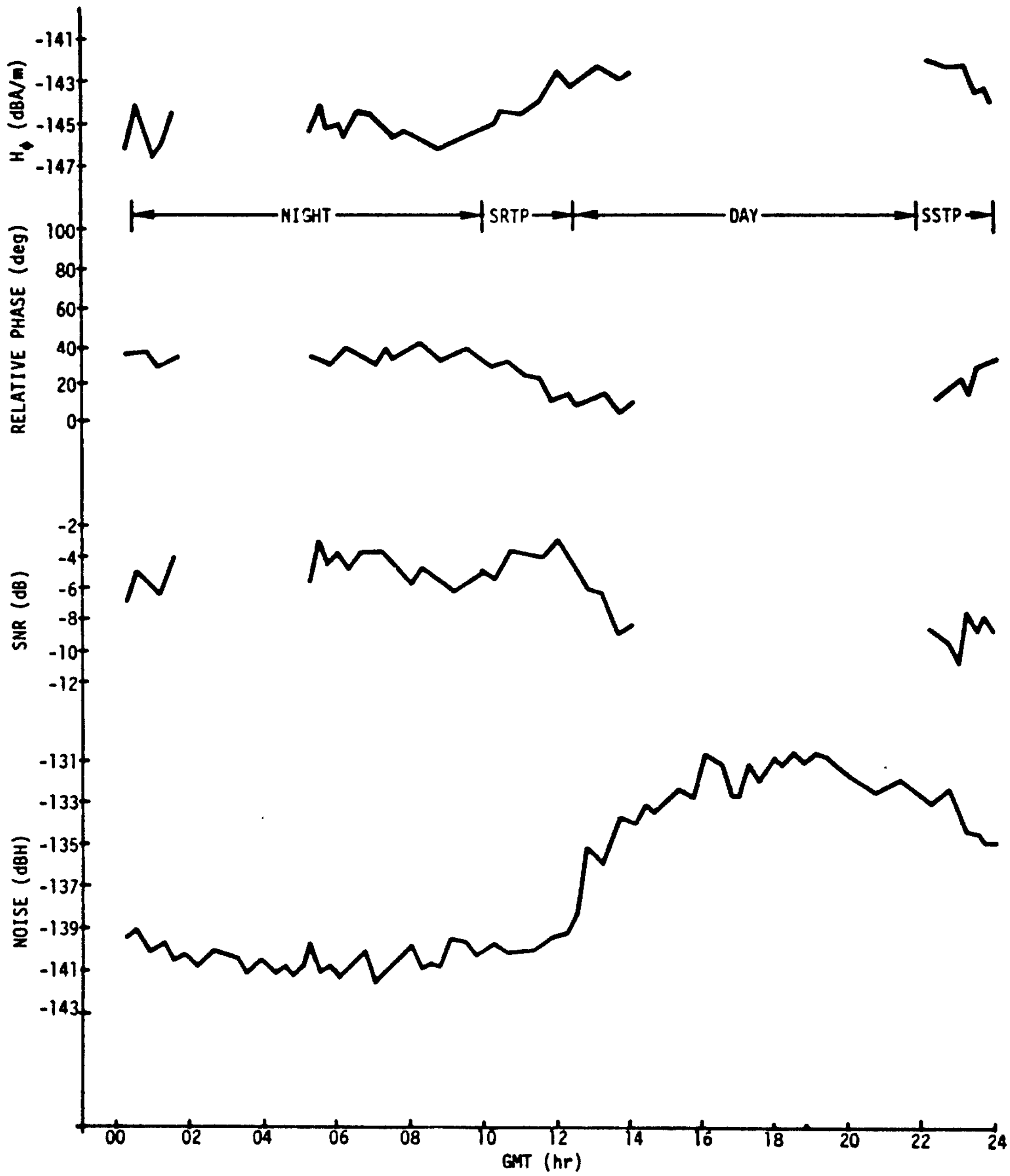

Figure B-13. Connecticut Data Versus GMT
(ψ = 291 deg), 14 October 1977

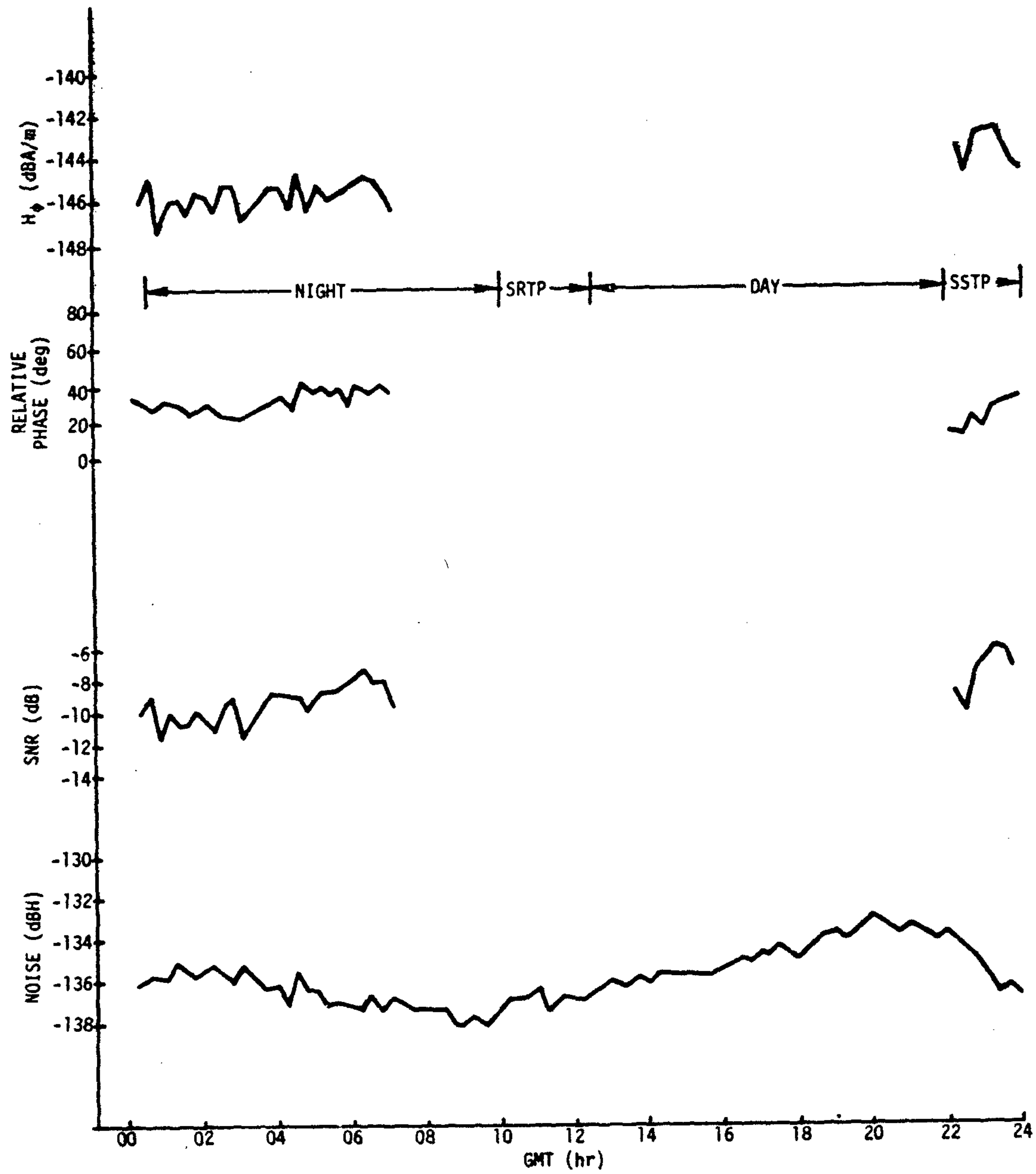

Figure B-14. Connecticut Data Versus GMT
(ψ = 291 deg), 15 October 1977

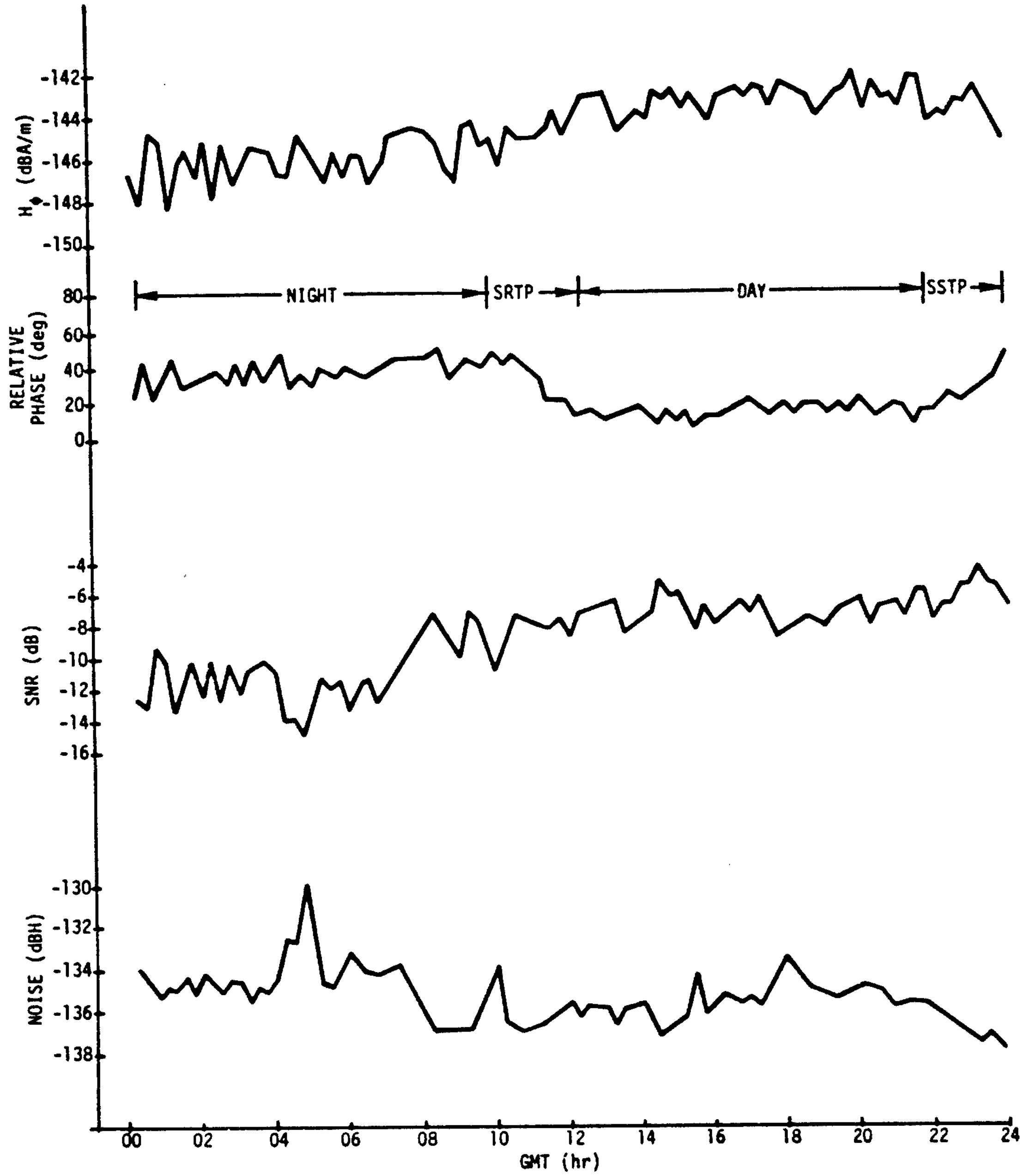

Figure B-15. Connecticut Data Versus GMT (ψ = 291 deg), 17 October 1977

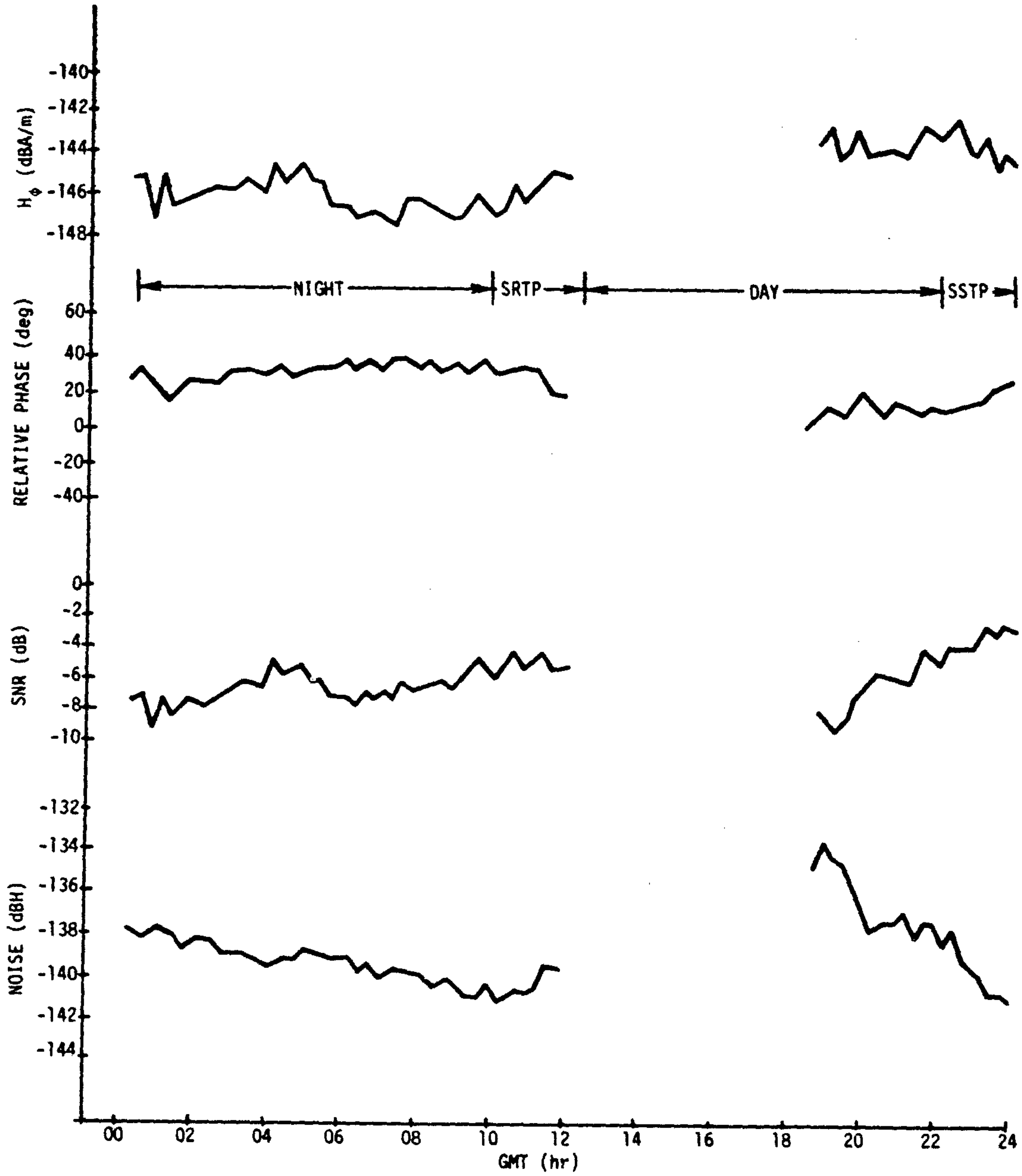

Figure B-16. Connecticut Data Versus GMT
(ψ = 21 deg), 18 October 1977

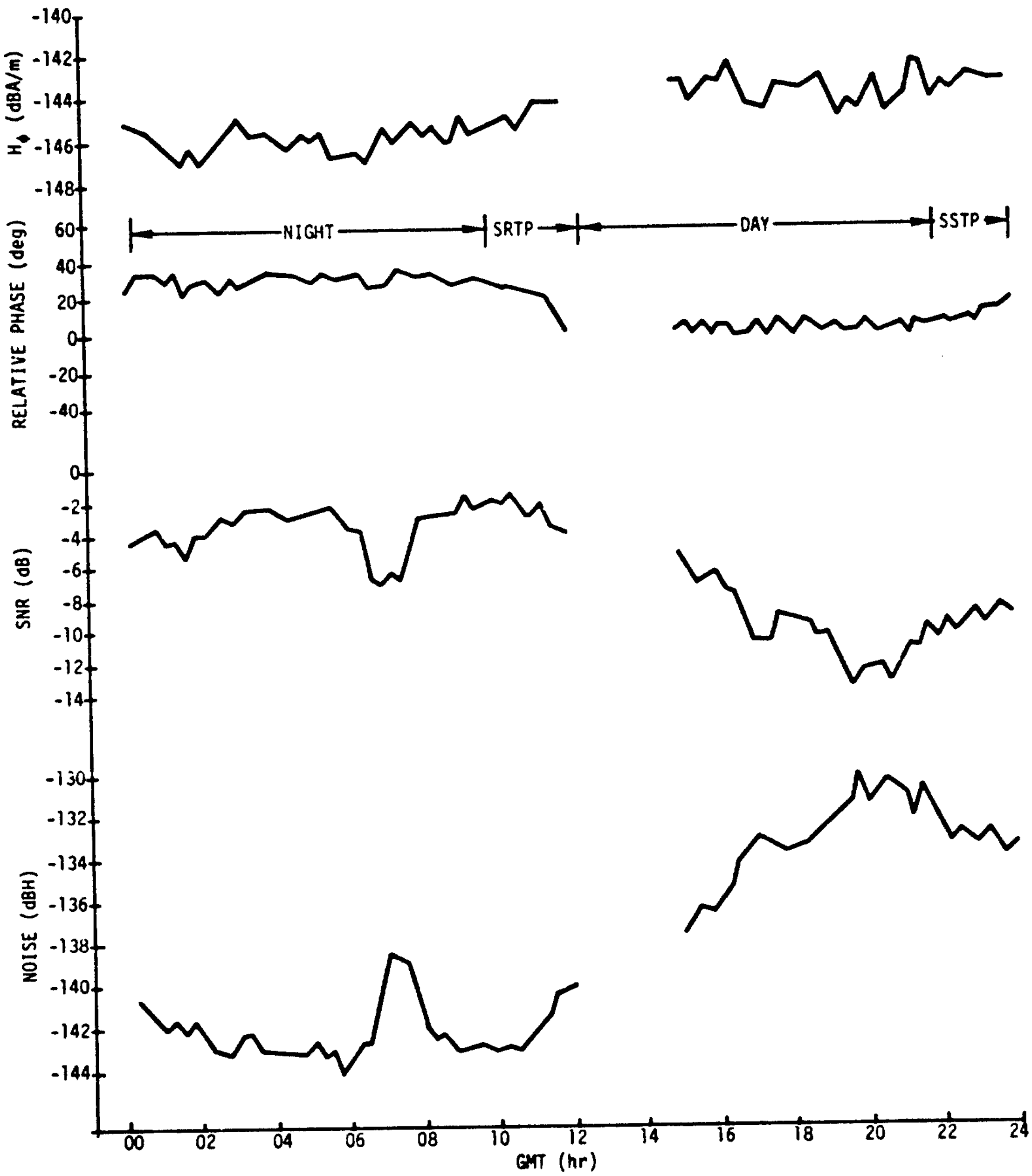

Figure B-17. Connecticut Data Versus GMT
(ψ = 21 deg), 19 October 1977

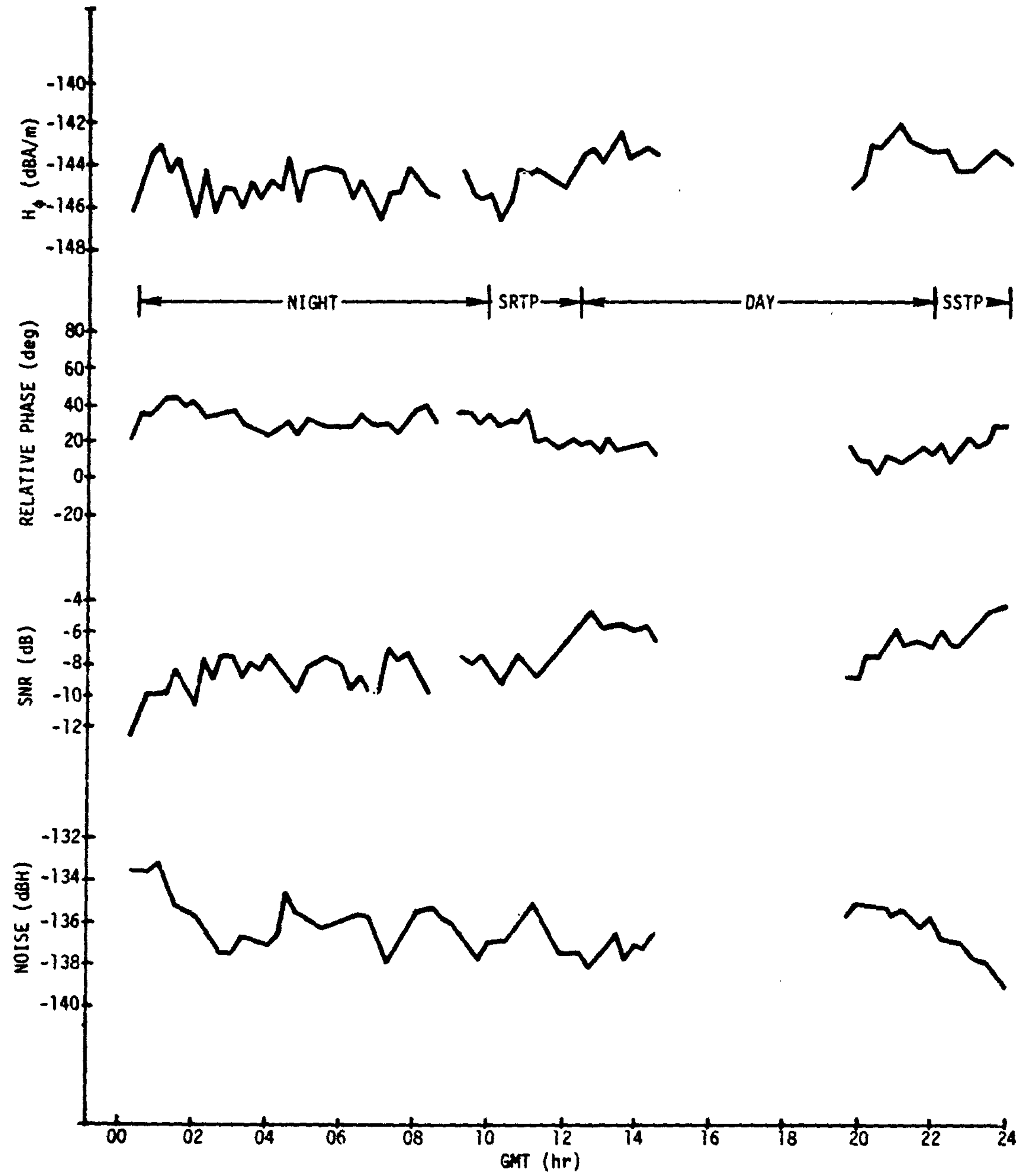

Figure B-18. Connecticut Data Versus GMT
(ψ = 21 deg), 20 October 1977

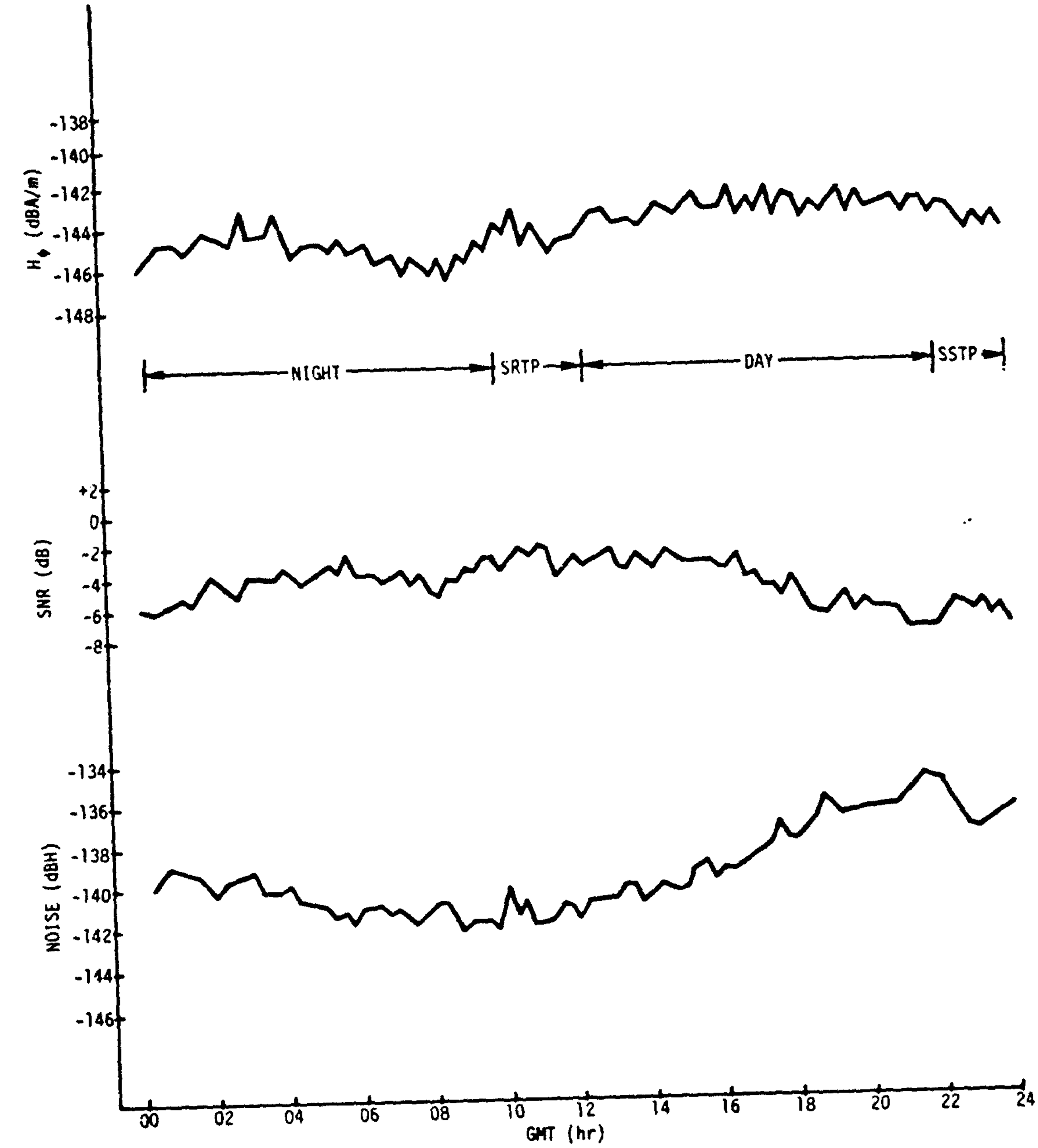

Figure B-19. Connecticut Data Versus GMT
(ψ = 21 deg), 21 October 1977

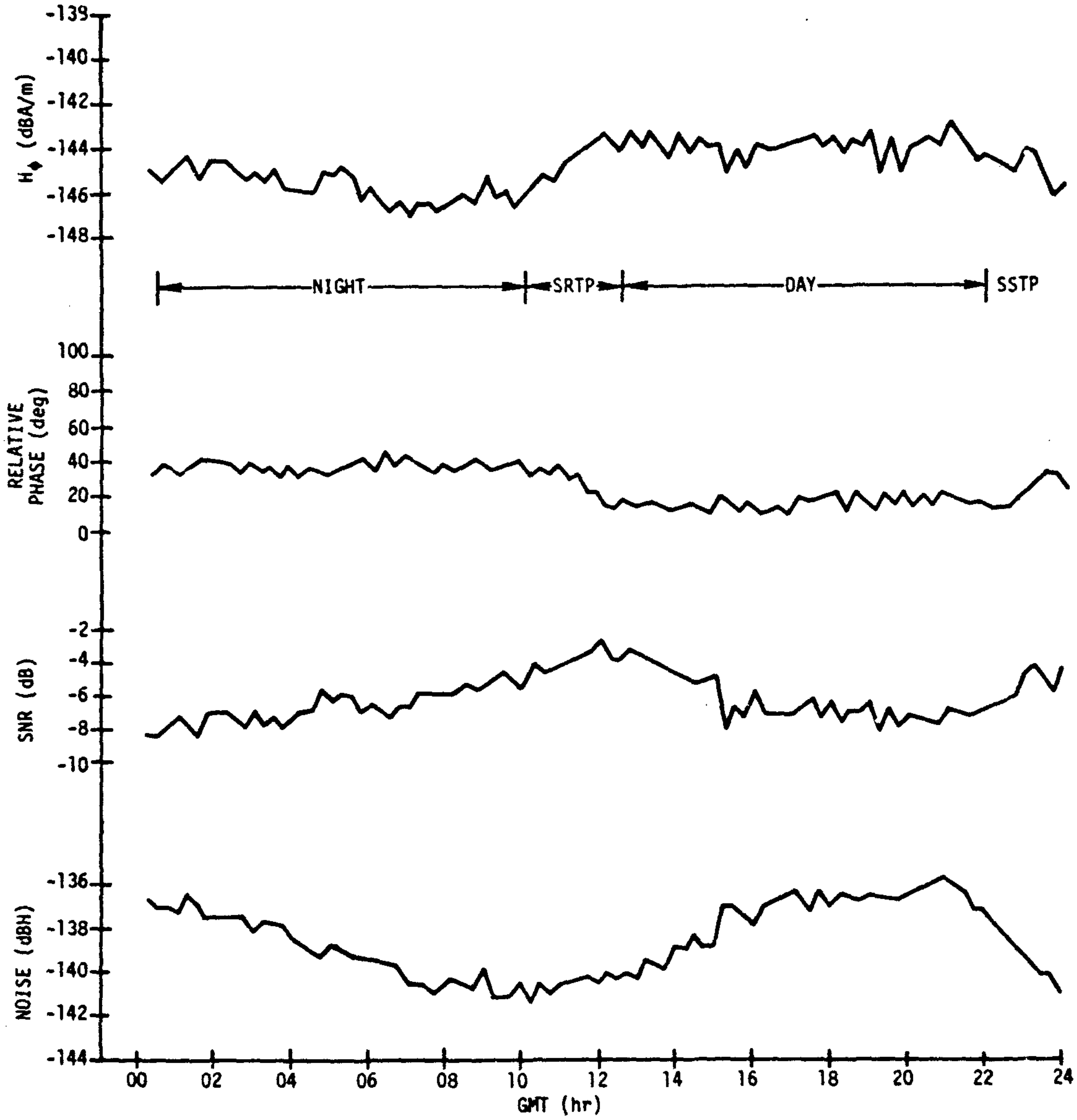

Figure B-20. Connecticut Data Versus GMT
(ψ = 21 deg), 22 October 1977

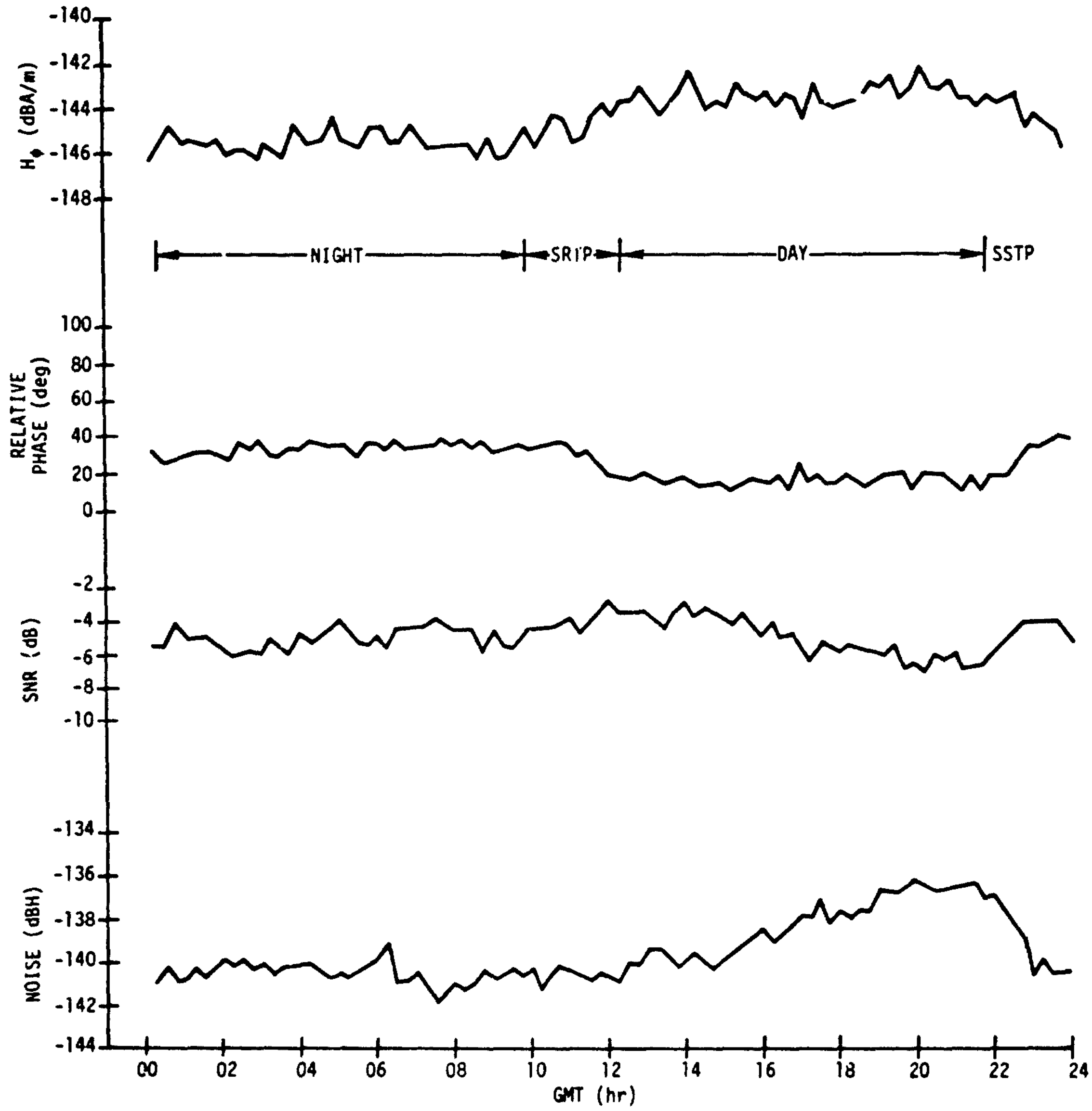

Figure B-21. Connecticut Data Versus GMT
(ψ = 21 deg), 23 October 1977

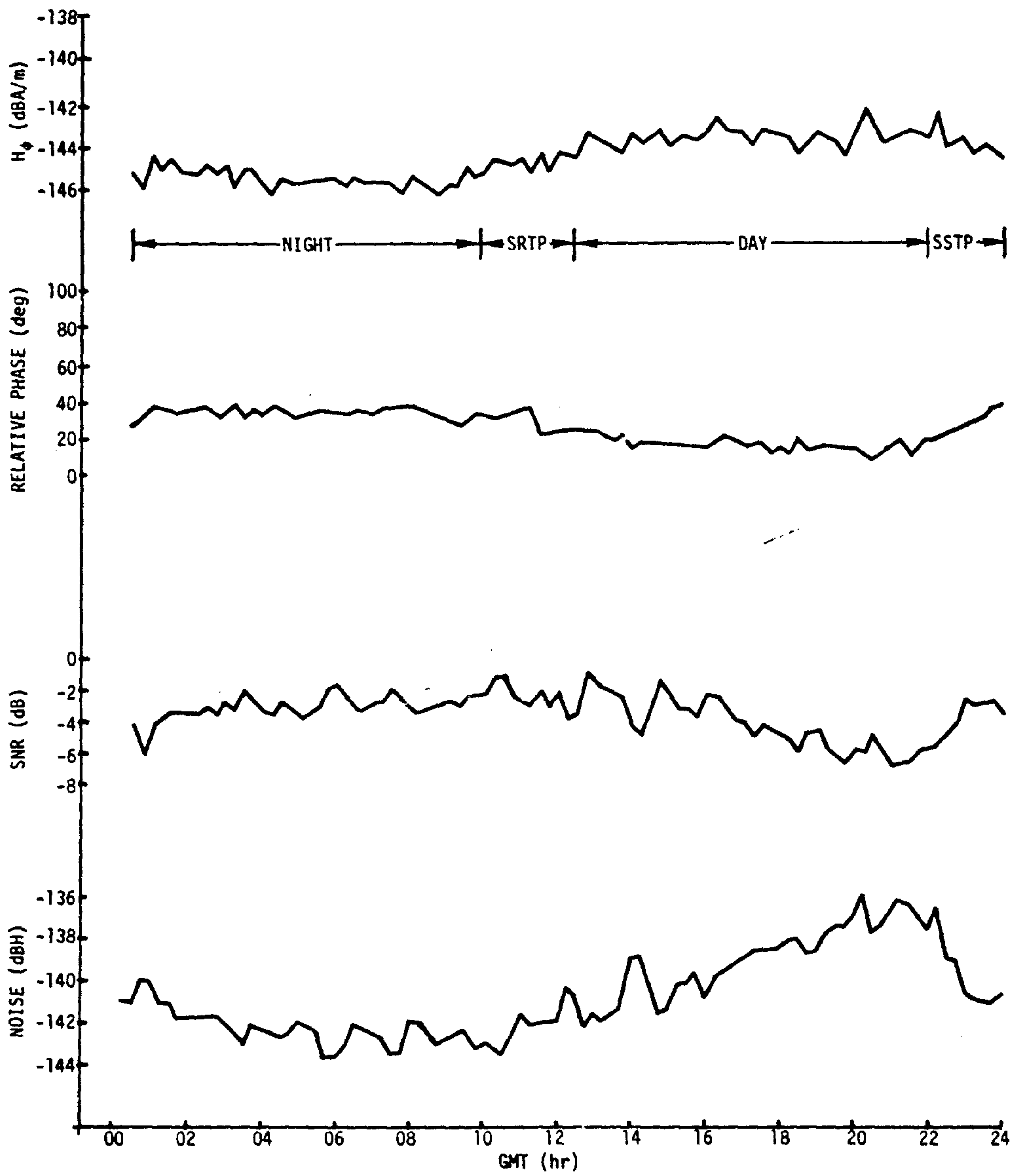

Figure B-22. Connecticut Data Versus GMT
(ψ = 21 deg), 24 October 1977

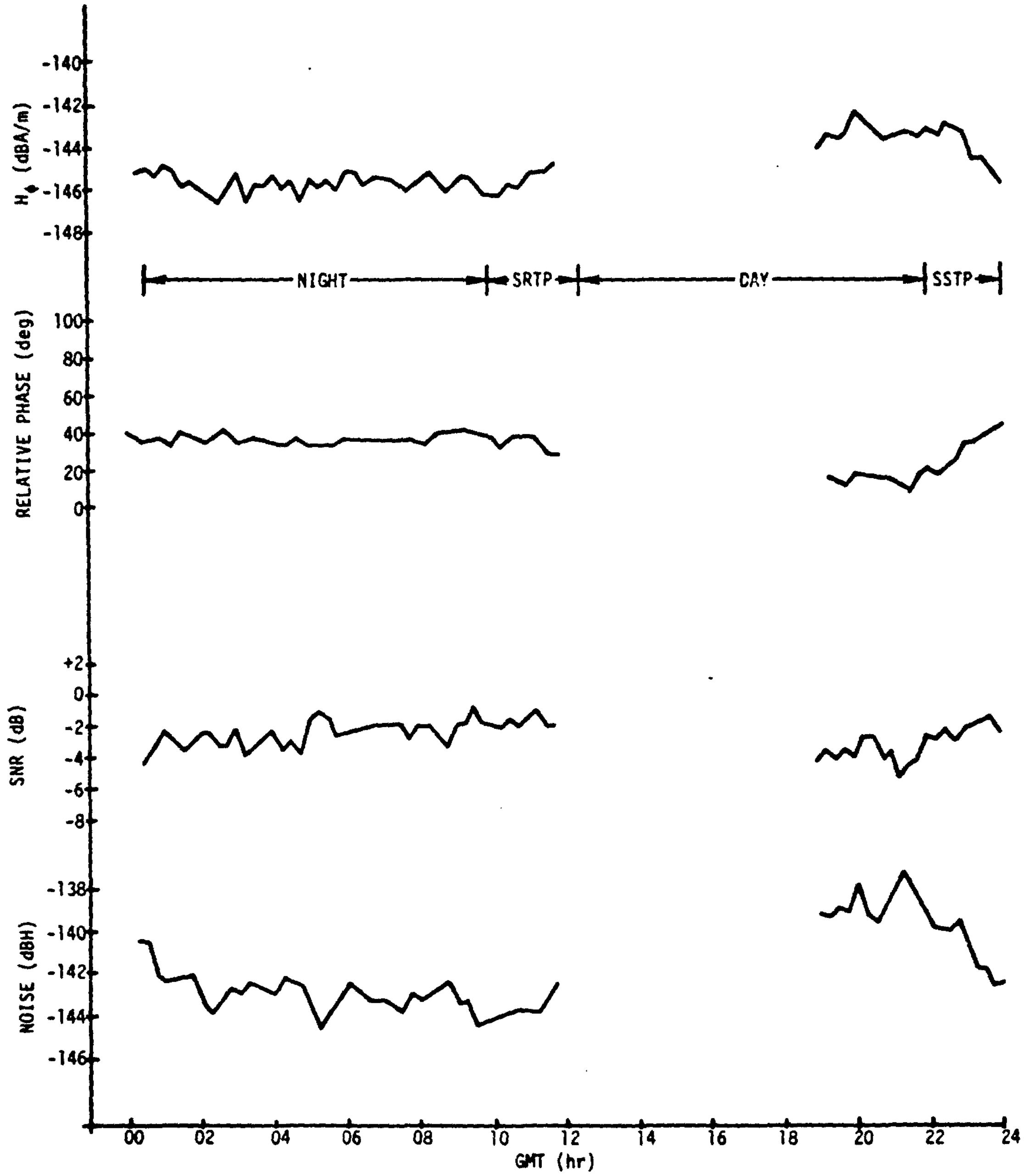

Figure B-23. Connecticut Data Versus GMT
(ψ = 21 deg), 25 October 1977

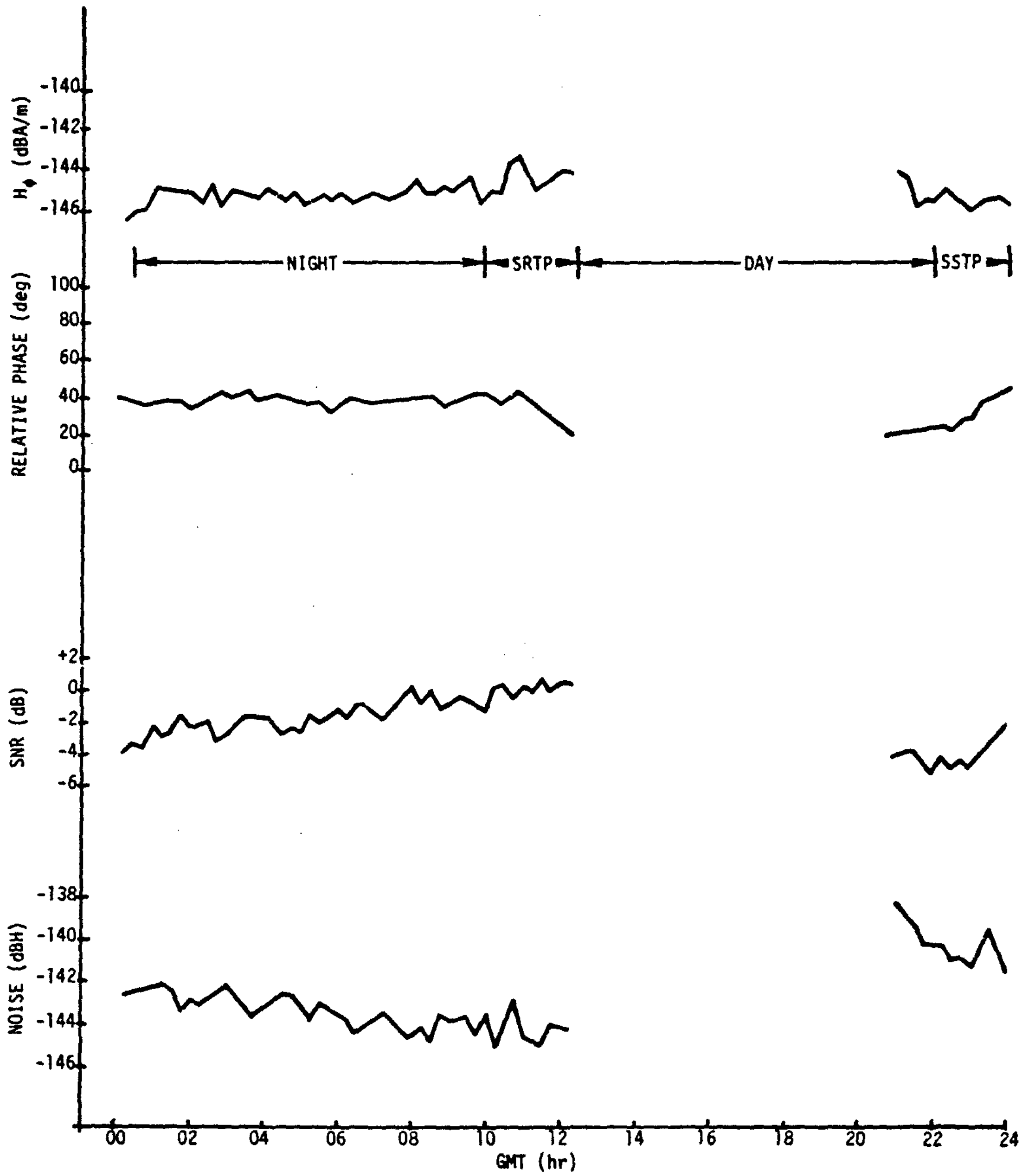

Figure B-24. Connecticut Data Versus GMT
(ψ = 21 deg), 26 October 1977

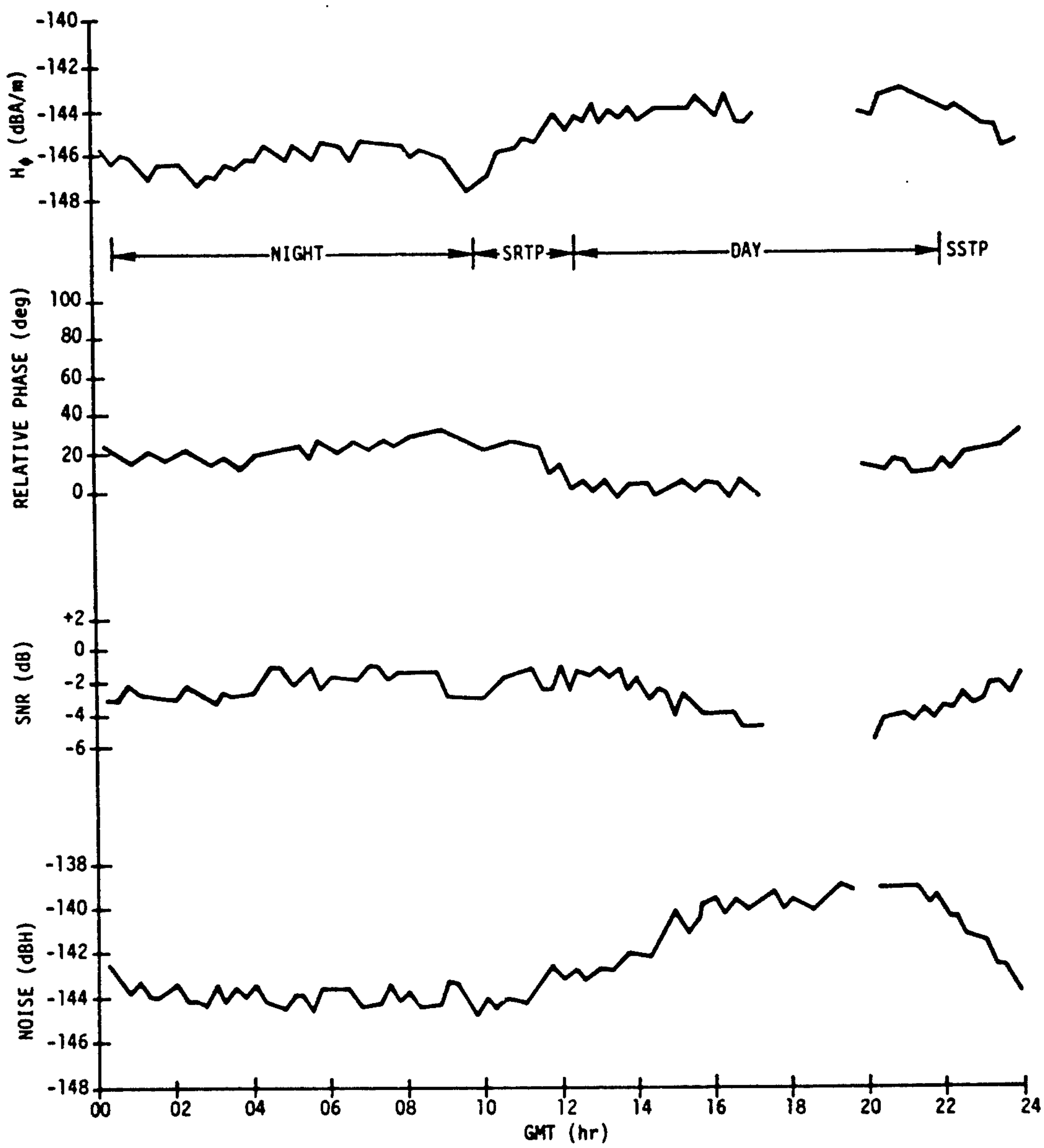

Figure B-25. Connecticut Data Versus GMT
(ψ = 21 deg), 27 October 1977

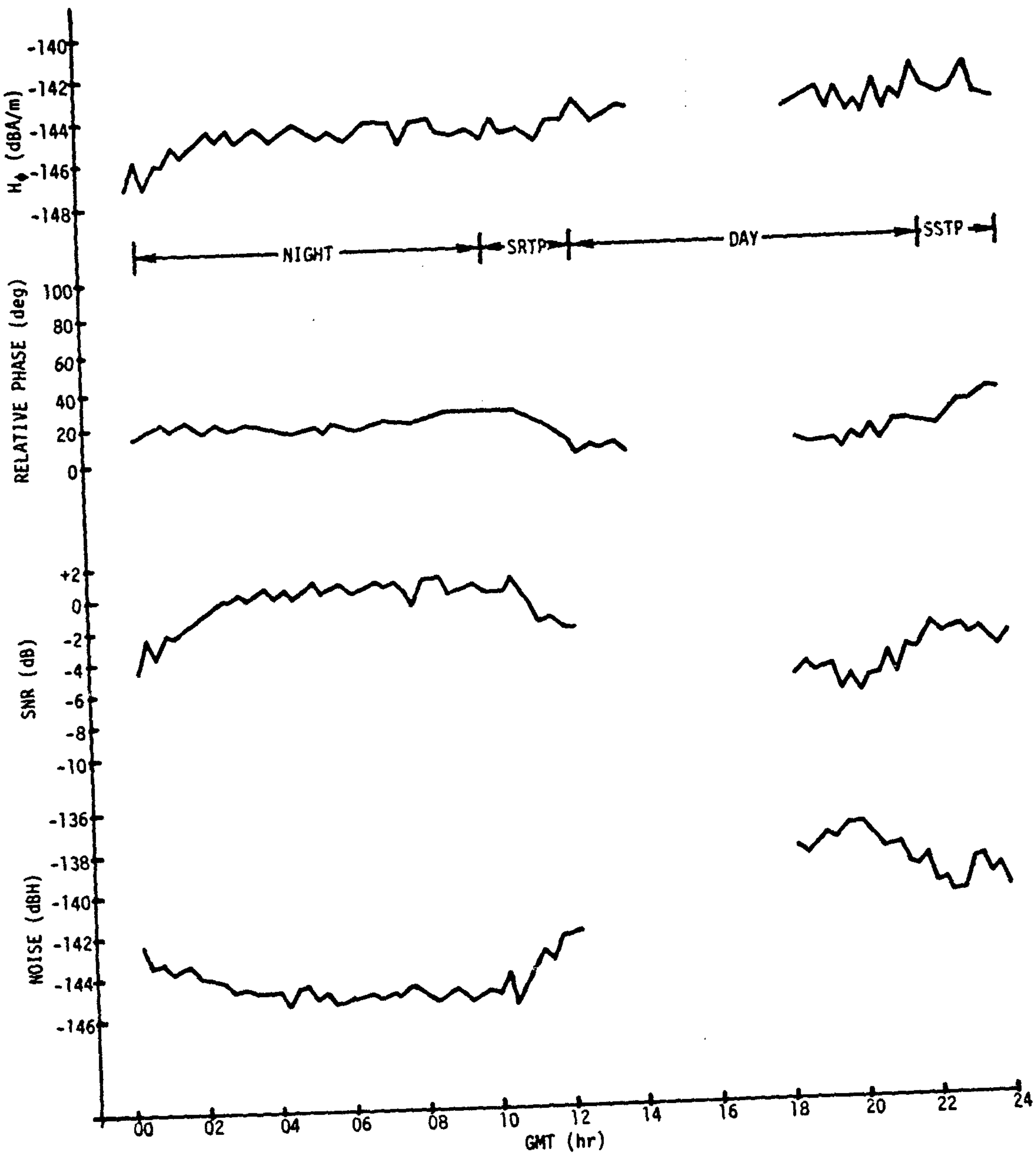

Figure B-26. Connecticut Data Versus GMT
(ψ = 21 deg), 28 October 1977

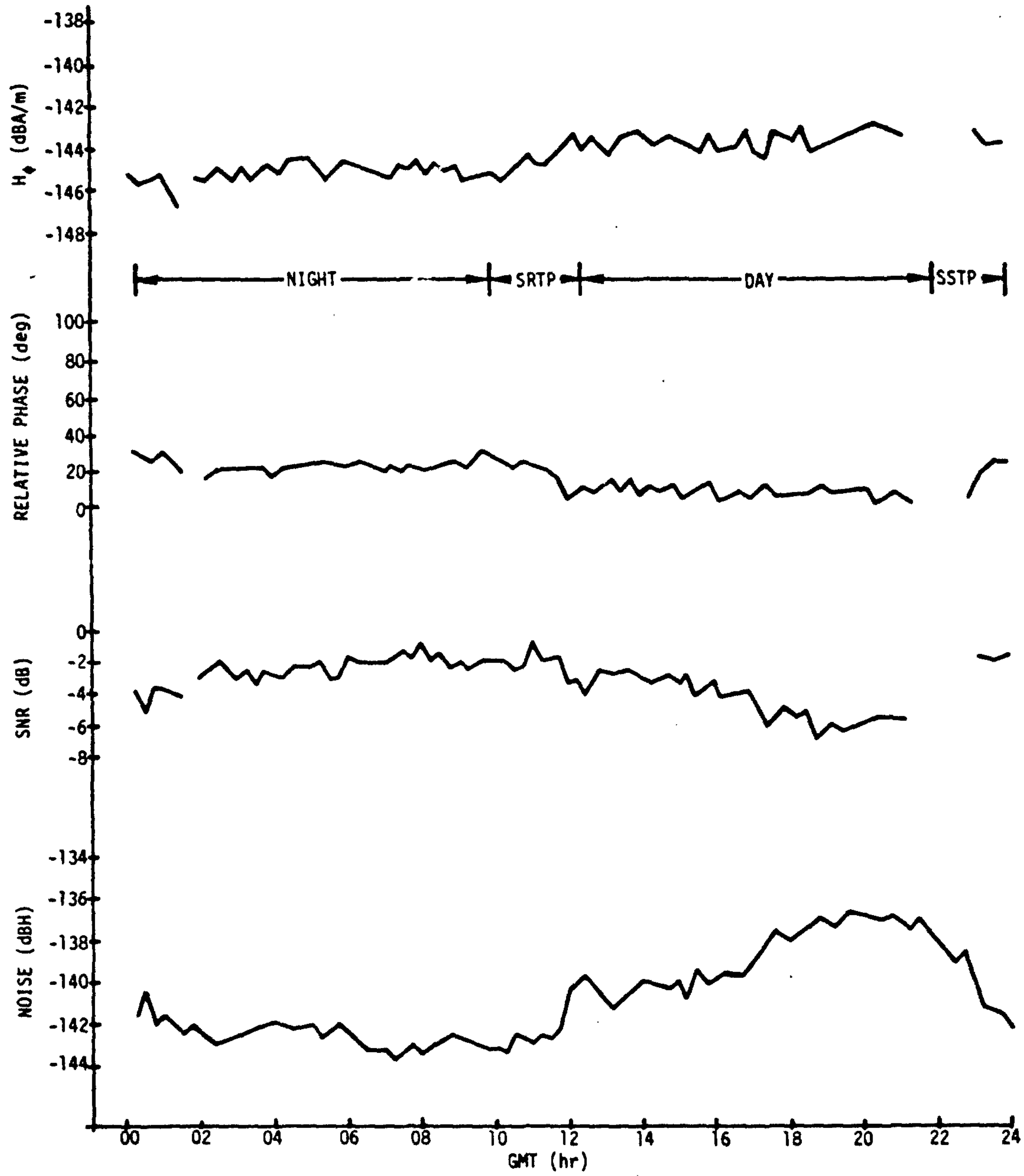

Figure B-27. Connecticut Data Versus GMT (ψ = 21 deg), 29 October 1977

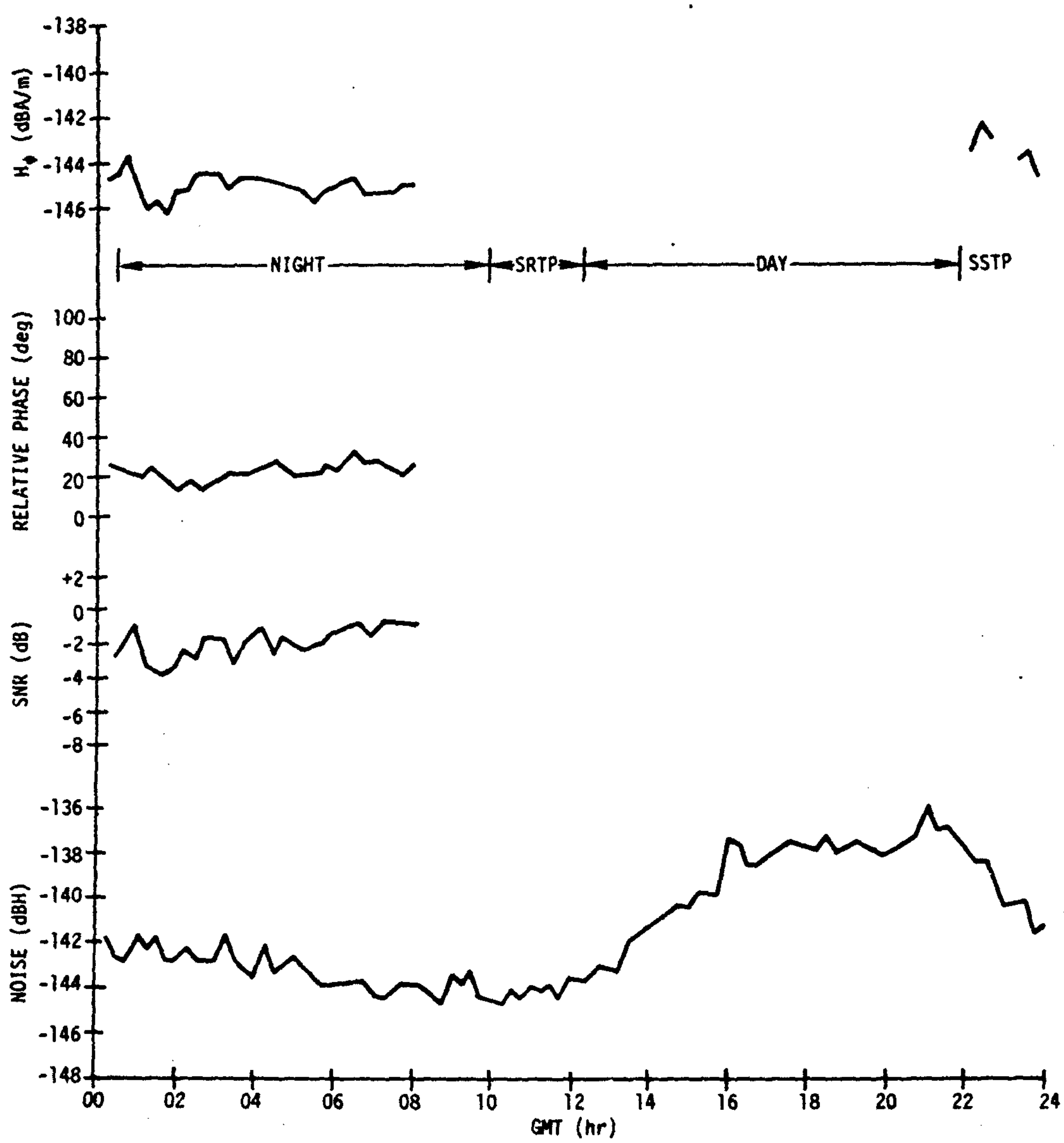

Figure B-28. Connecticut Data Versus GMT
(ψ = 21 deg), 30 October 1977

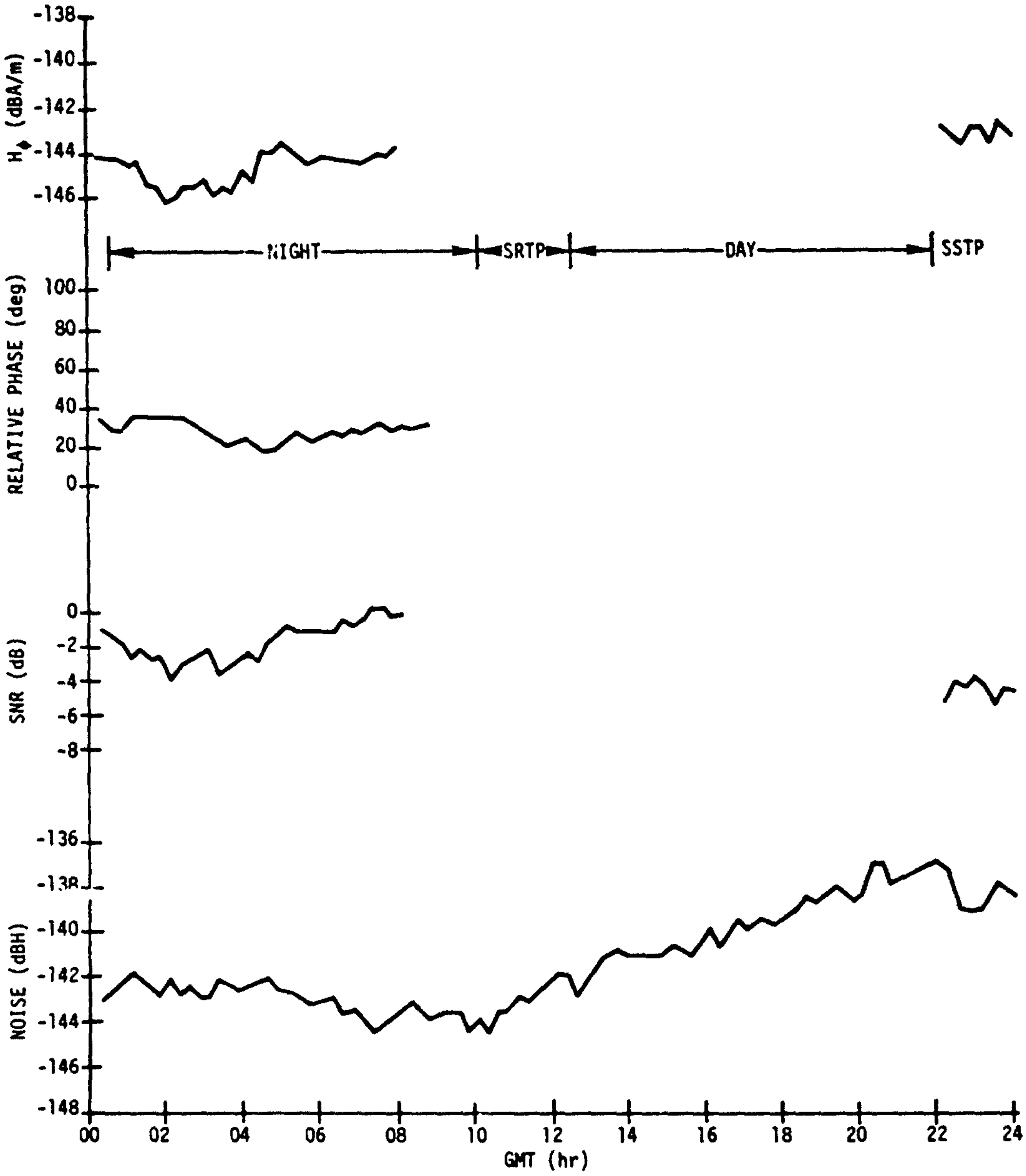

Figure B-29. Connecticut Data Versus GMT
(ψ = 291 deg), 31 October 1977

Appendix C

WESTERN-PACIFIC-AREA SUBMARINE DAILY DATA

The daily 30 September to 5 November Western-Pacific-area submarine field-strength (both amplitude and relative phase), effective-noise, and SNR values are plotted versus GMT in figures C-1 through C-25. The WTF antenna phasing angle (ψ) was 291 deg from 30 September through 17 October and 21 deg from 22 to 30 October. The transmitting frequency was 76 ±4 Hz.

For long WTF/Western-Pacific paths (figures C-1 through C-17), the measured nighttime field strength will be greater than the daytime field strength because of tne substantial difference in attenuation rates (1.5 dB/Mm compared with 0.8 to 0.9 dB/Mm). Interference between the direct and "round-the-world" waves also may be present, resulting in even lower measured daytime field strengths.

From 30 September to 17 October, amplitude peak-to-trough variations of 9 dB or greater occurred during 7 of the 16 measurement days, on 1, 3, 7, 8, 12, 13, and 14 October (figures C-2, C-4, C-7, C-8, C-12, C-13, and C-14). During six of these seven days, the minimum field-strength value was measured during all daytime propagation conditions. On 12 October (figure C-12), the minimum field-strength value was measured during the 0630 to 0700 portion of the SSTP.

The 30 September to 17 October night-to-day relative-phase variation was fairly regular (i.e., $\Delta\phi$ ~164 ±23 deg), with the largest variation (199 deg) occurring on 9 October (figure C-9) and the smallest variation (137 deg) occurring on 30 September (figure C-1).

The 22 October to 5 November night-to-day relative-phase variation was also fairly regular (i.e., $\Delta\phi$ ~95 ±19 deg). The largest variation (113 deg) occurred on 4 November (figure C-24), while the smallest variation (73 deg) occurred on 27 October (figure C-21).

The largest daily peak-to-trough variations in the effective noise (~20 dB) were measured during 10 and 12 October (figures C-10 and C-12), each being one day before the largest daily peak-to-trough variations measured in the North Atlantic.

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.

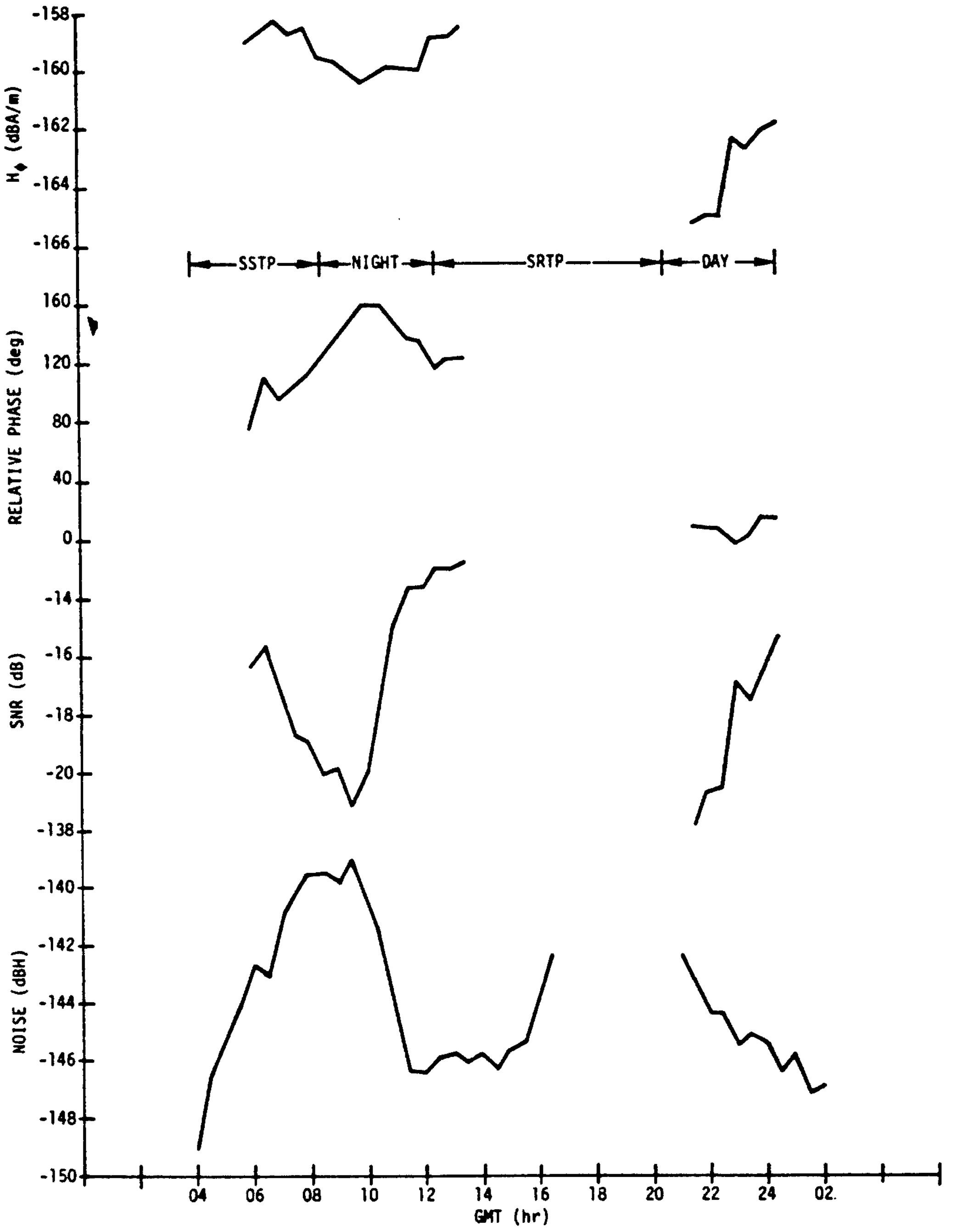

Figure C-1. Western-Pacific-Area Submarine Data Versus GMT (ψ = 291 deg), 30 September 1977

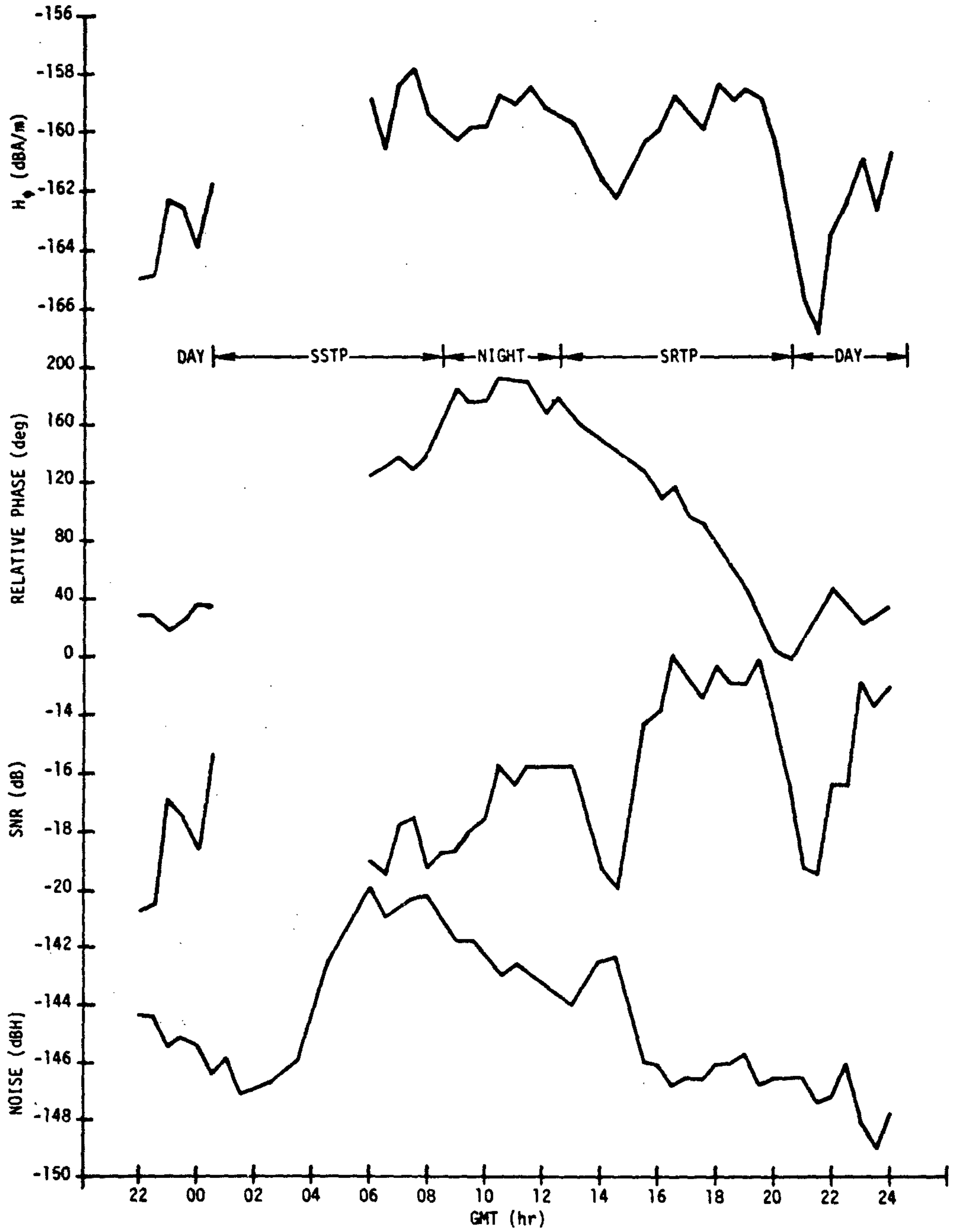

Figure C-2. Western-Pacific-Area Submarine Data Versus GMT (ψ = 291 deg), 1 October 1977

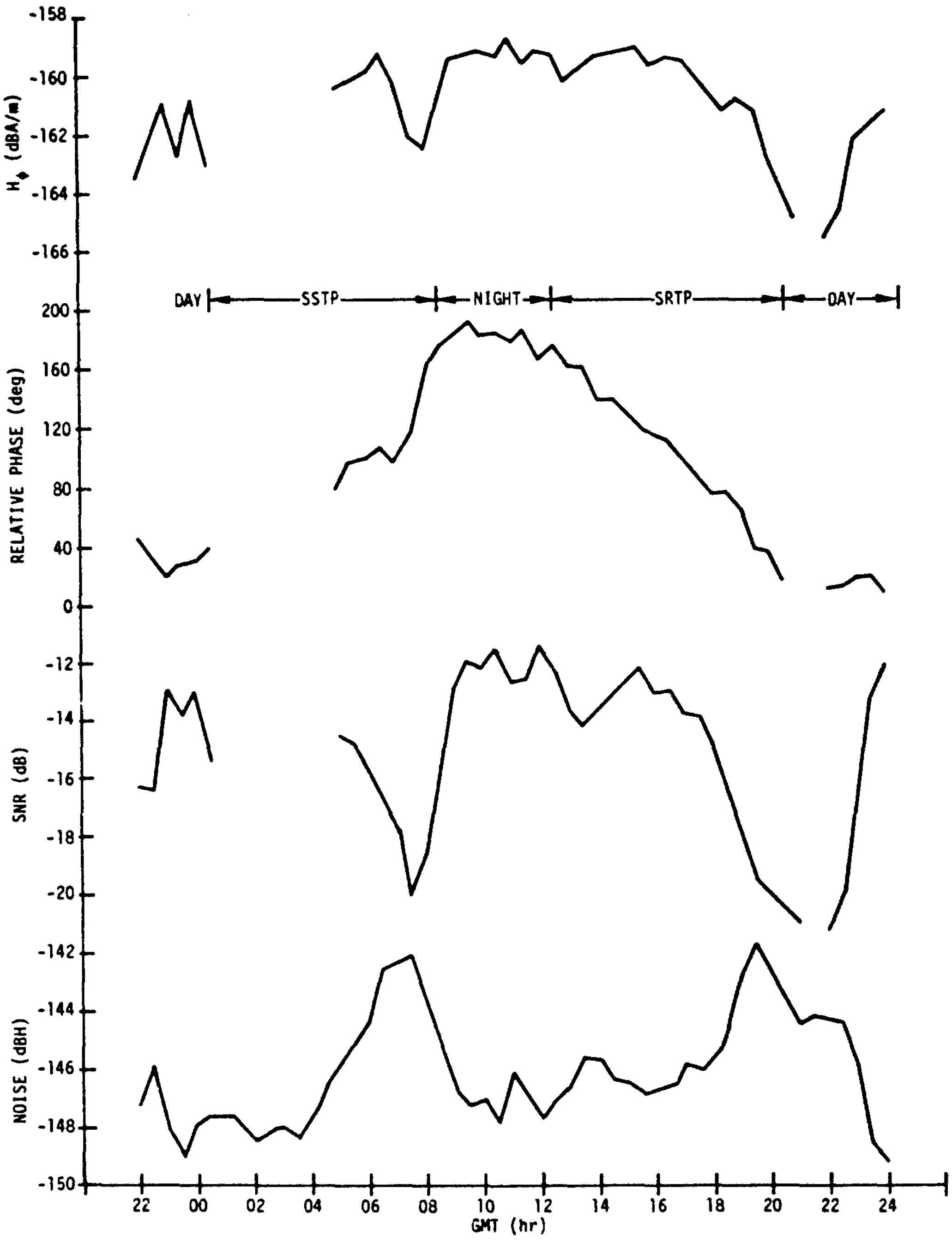

Figure C-3. Western-Pacific-Area Submarine Data Versus GMT (ψ = 291 deg), 2 October 1977

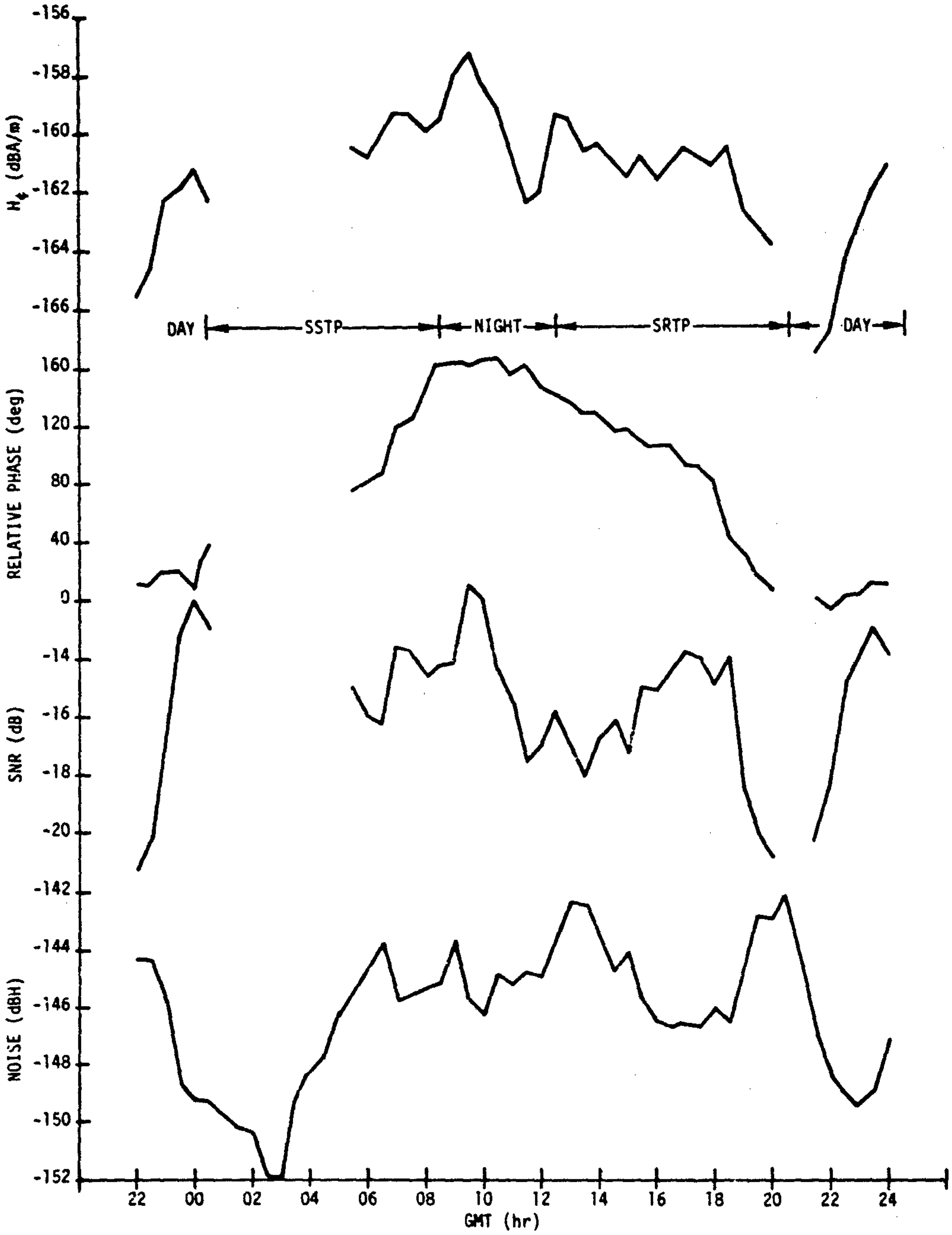

Figure C-4. Western-Pacific-Area Submarine Data Versus GMT (ψ = 291 deg), 3 October 1977

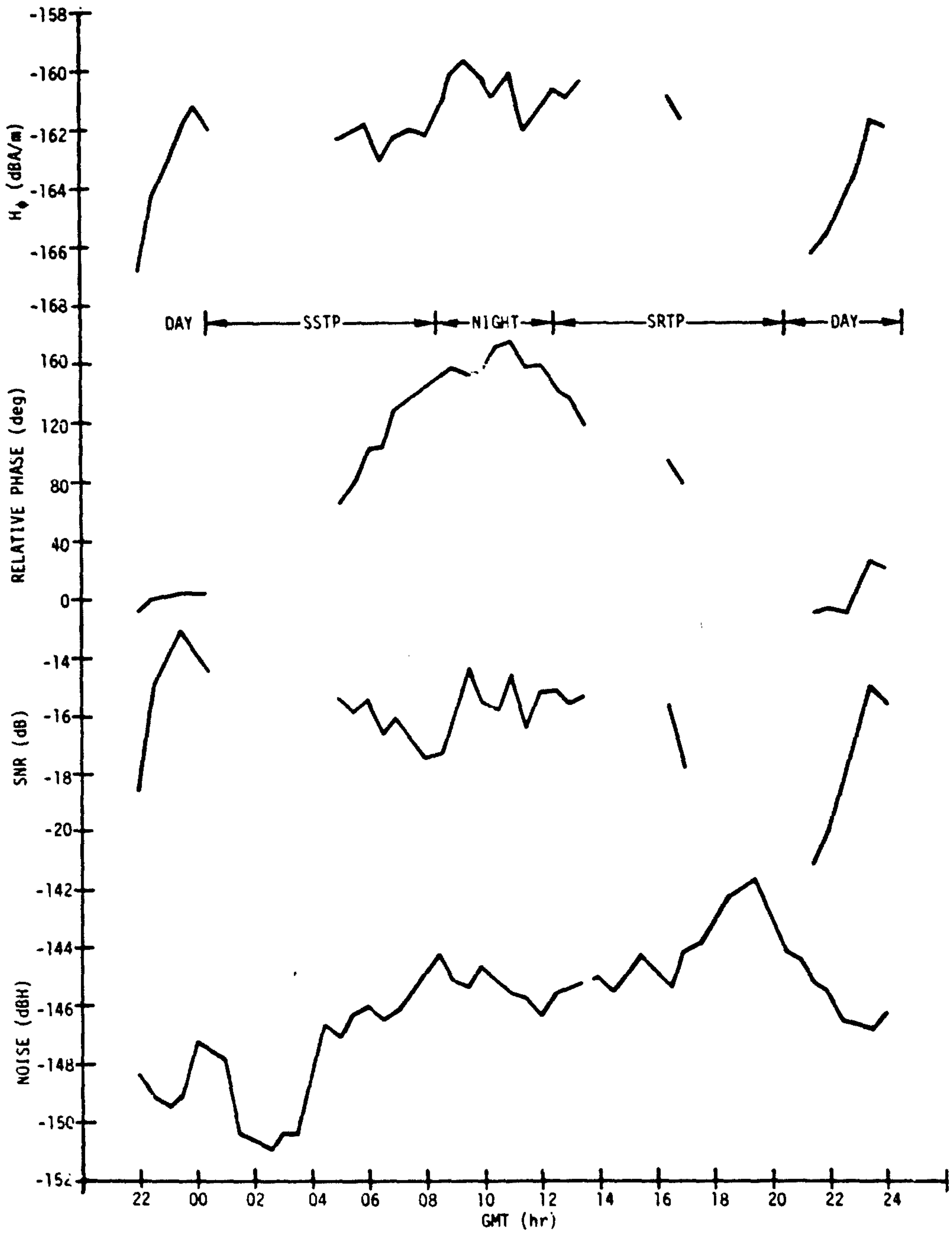

Figure C-5. Western-Pacific-Area Submarine Data Versus GMT (ψ = 291 deg), 4 October 1977

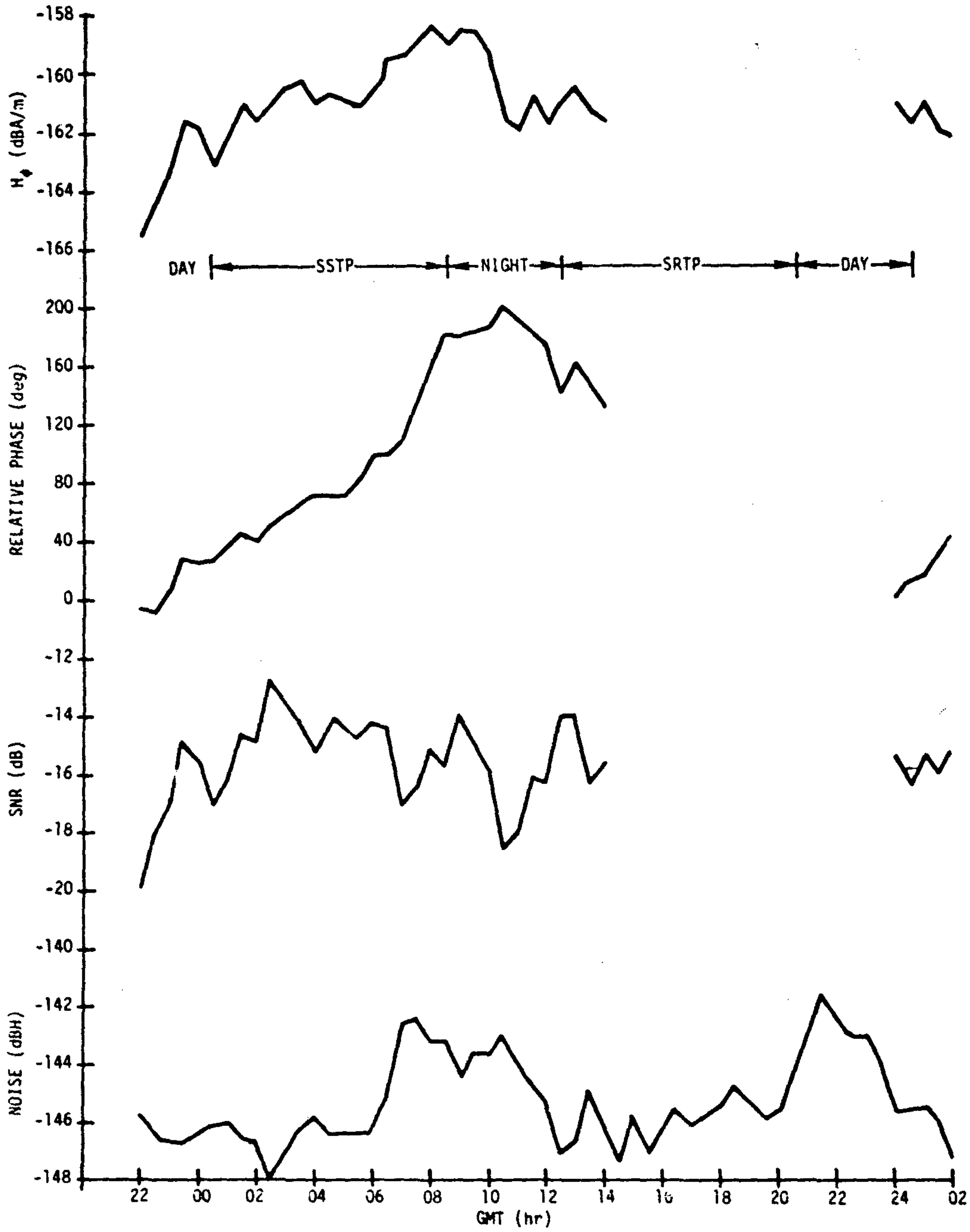

Figure C-6. Western-Pacific-Area Submarine Data Versus GMT (ψ = 291 deg), 5 October 1977

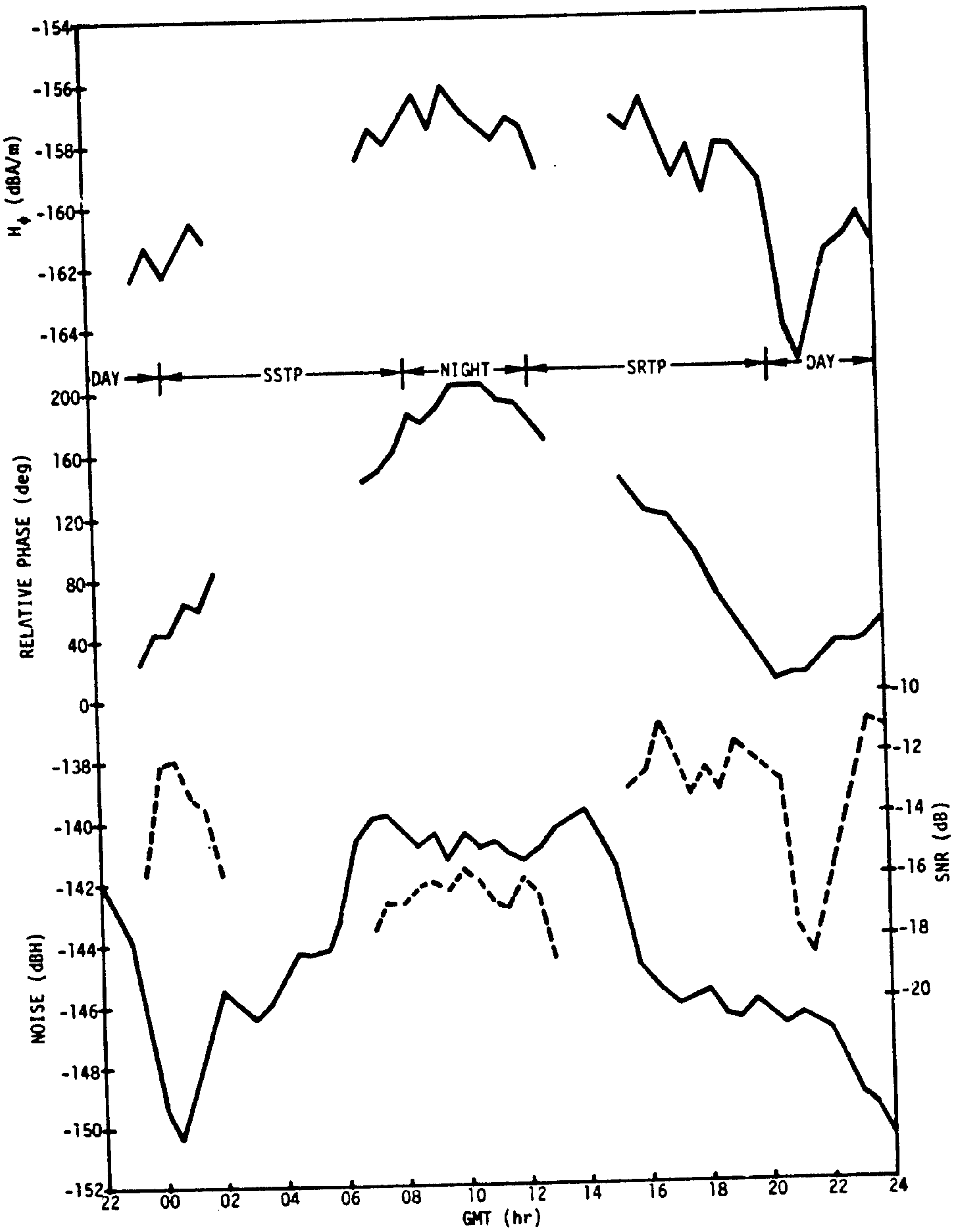

Figure C-7. Western-Pacific-Area Submarine Data Versus GMT (ψ = 291 deg), 7 October 1977

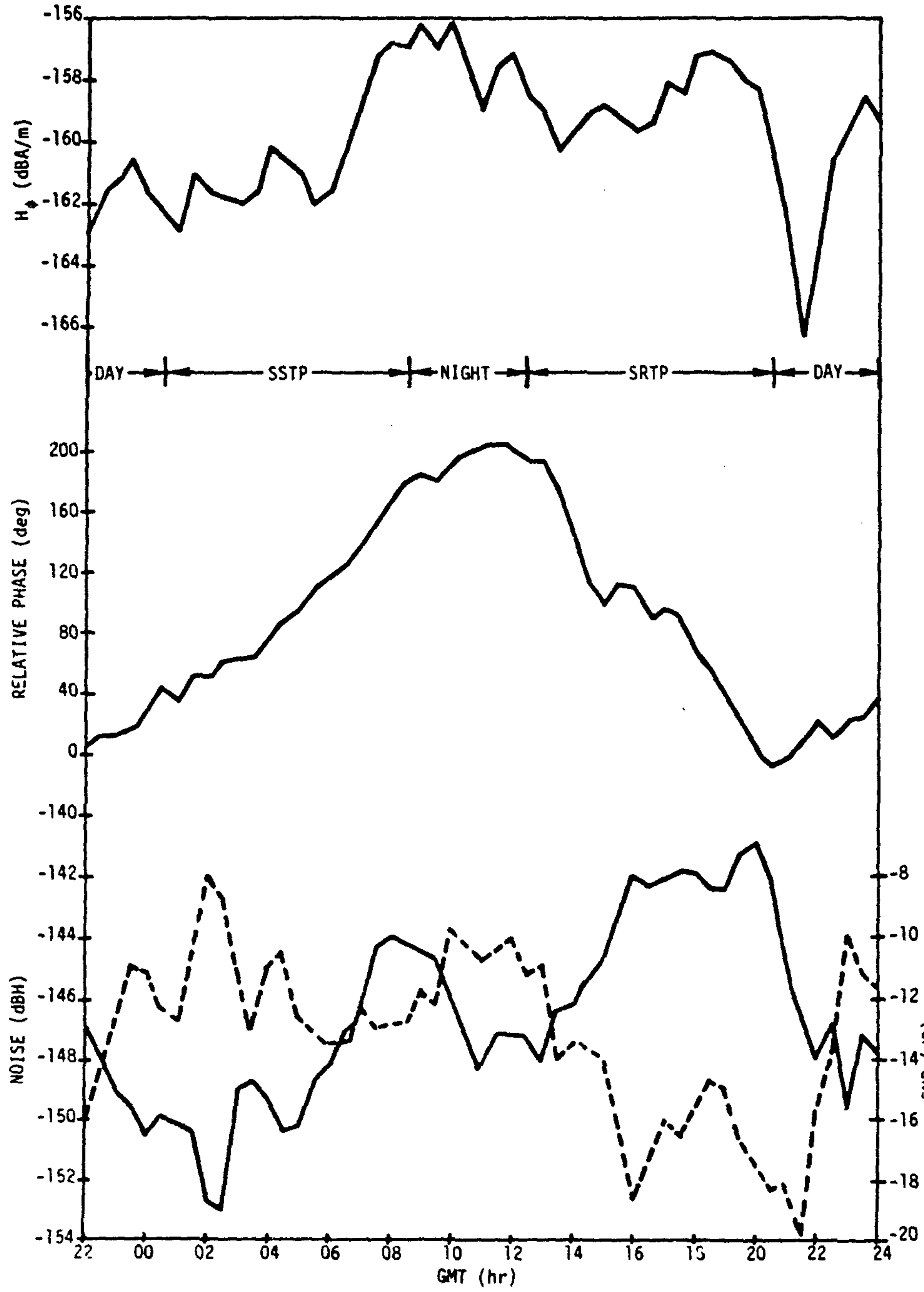

Figure C-8. Western-Pacific-Area Submarine Data Versus GMT (ψ = 291 deg), 8 October 1977

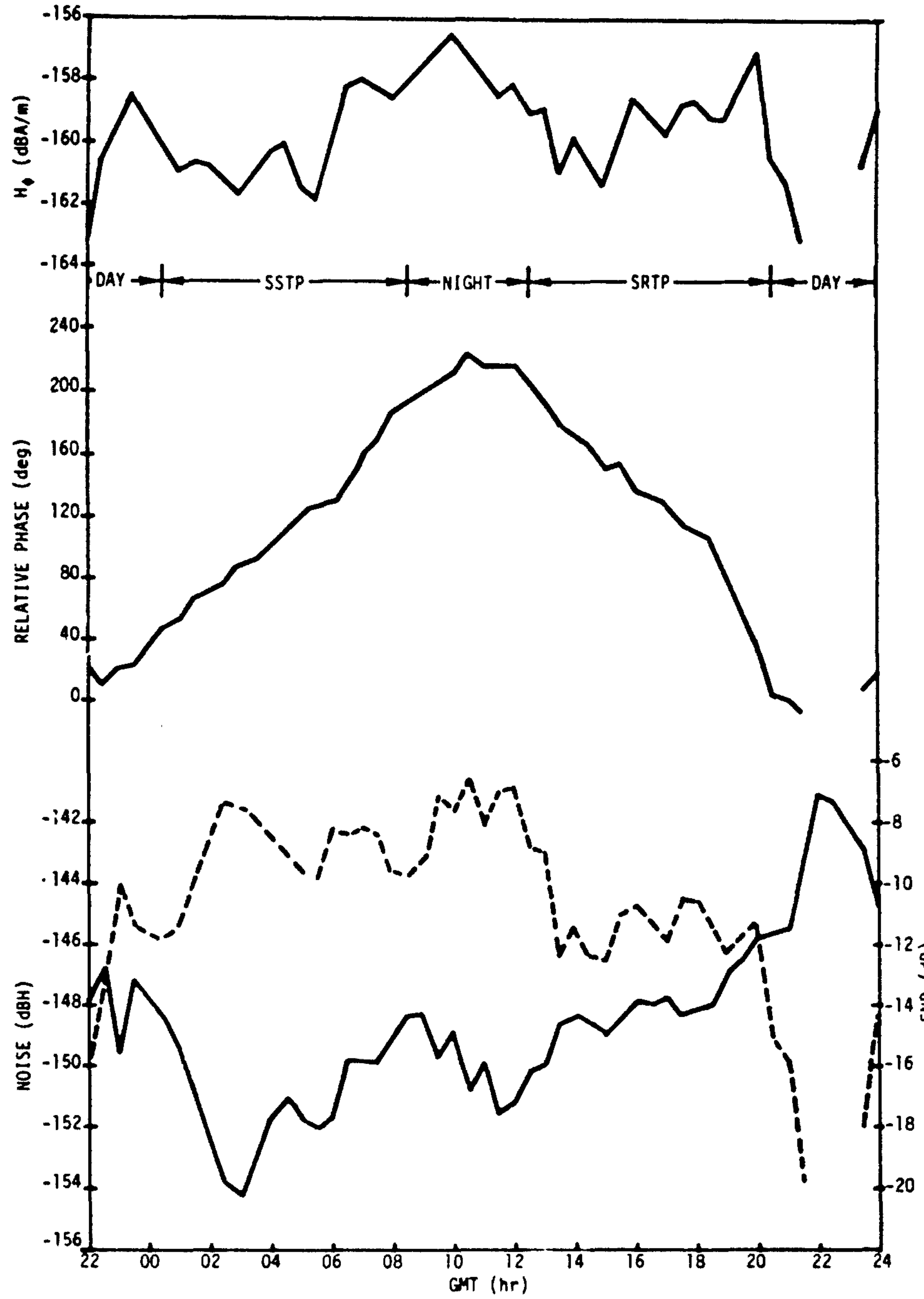

Figure C-9. Western-Pacific-Area Submarine Data Versus GMT (ψ = 291 deg), 9 October 1977

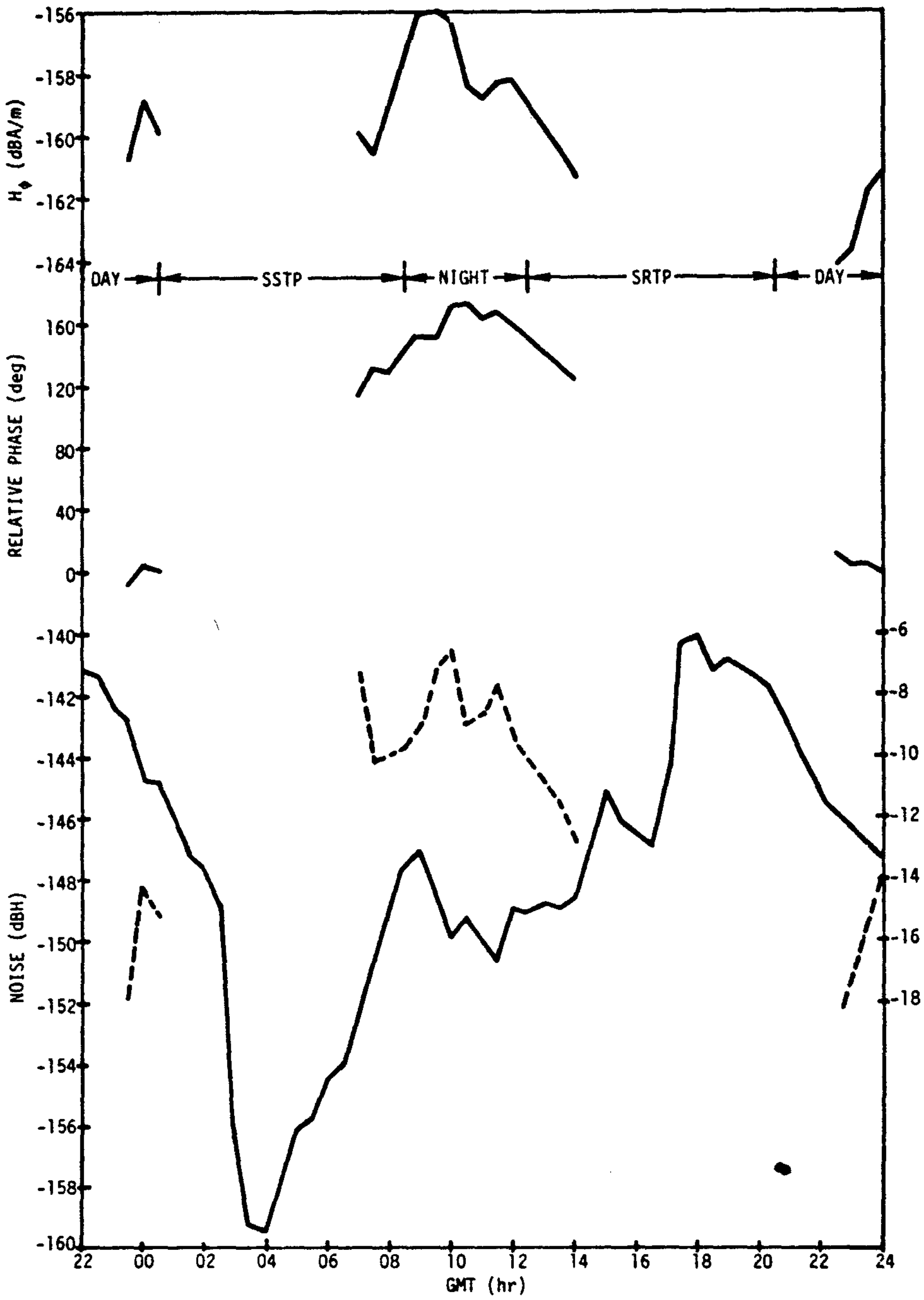

Figure C-10. Western-Pacific-Area Submarine Data Versus GMT (ψ = 291 deg), 10 October 1977

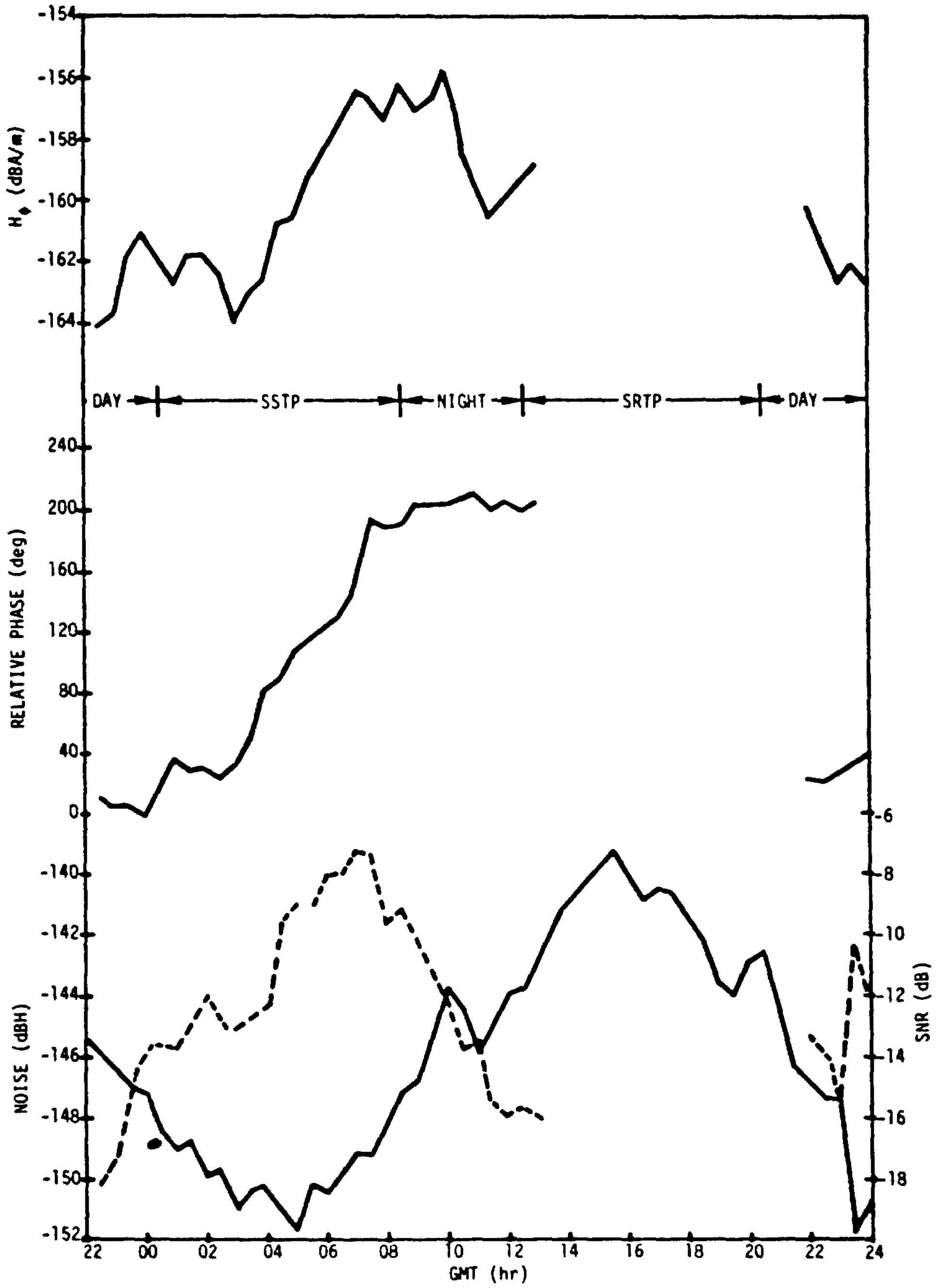

Figure C-11. Western-Pacific-Area Submarine Data Versus
GMT (ψ = 291 deg), 11 October 1977

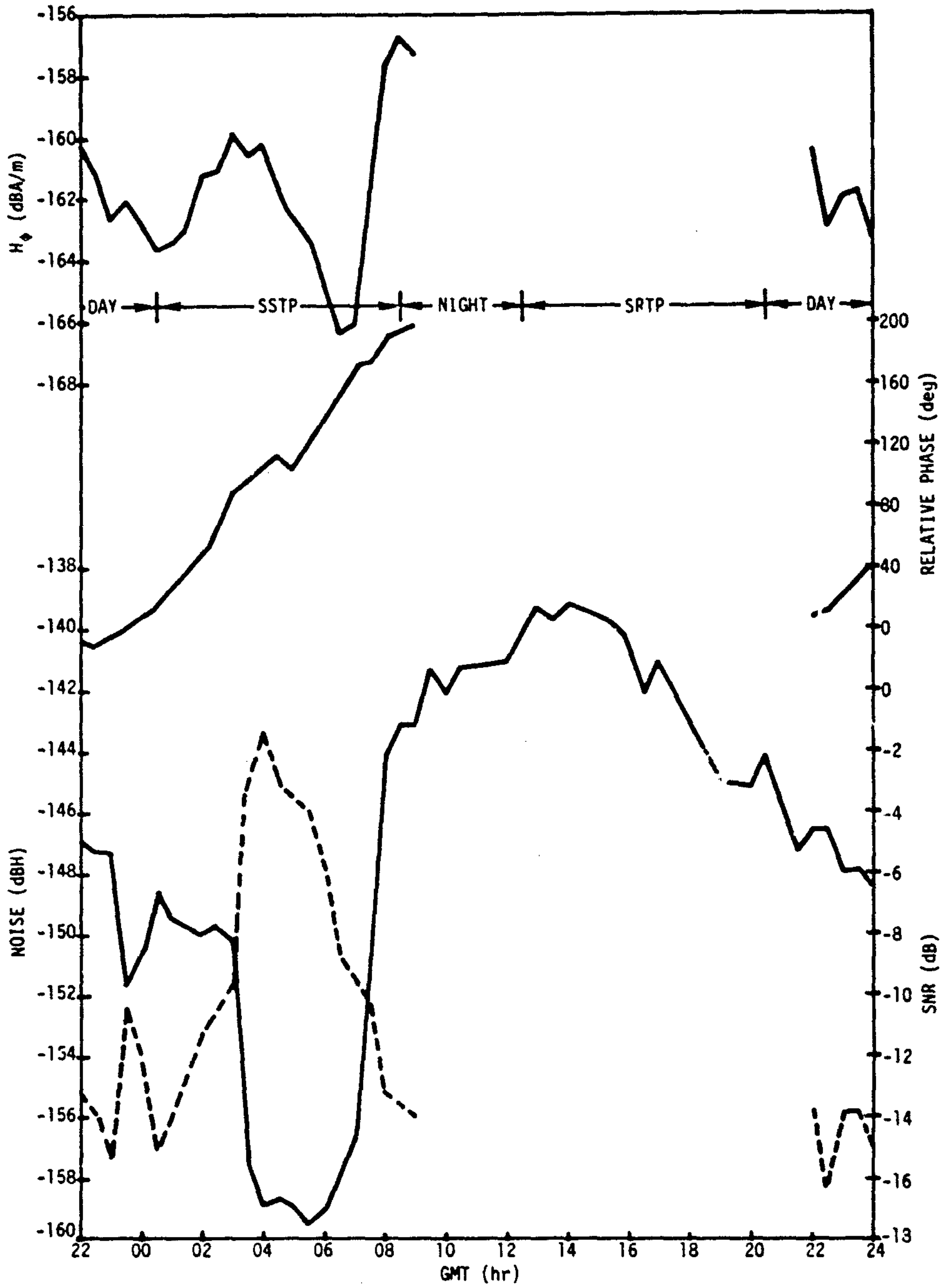

Figure C-12. Western-Pacific-Area Submarine Data Versus GMT (ψ = 291 deg), 12 October 1977

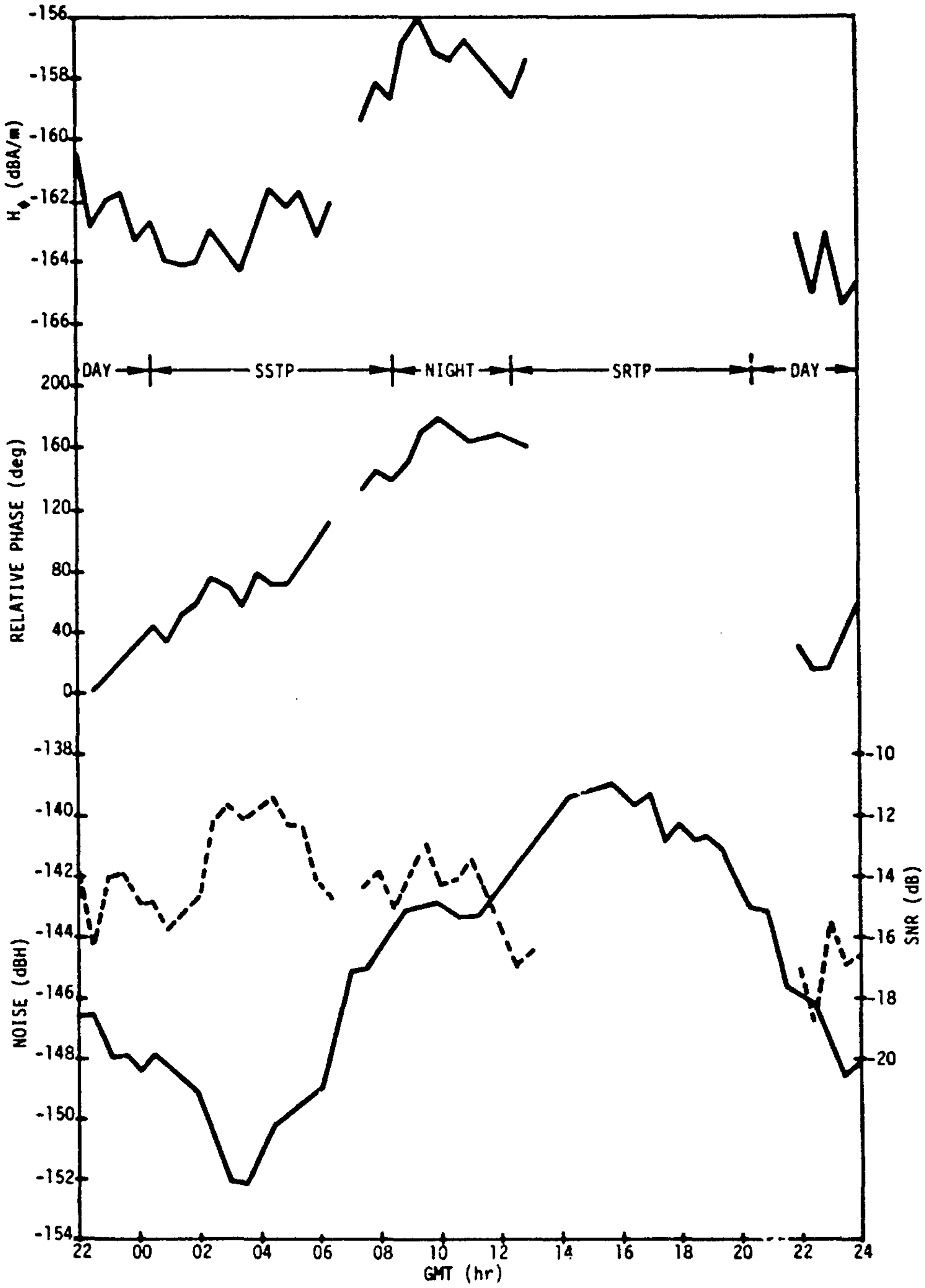

Figure C-13. Western-Pacific-Area Submarine Data Versus GMT (ψ = 291 deg), 13 October 1977

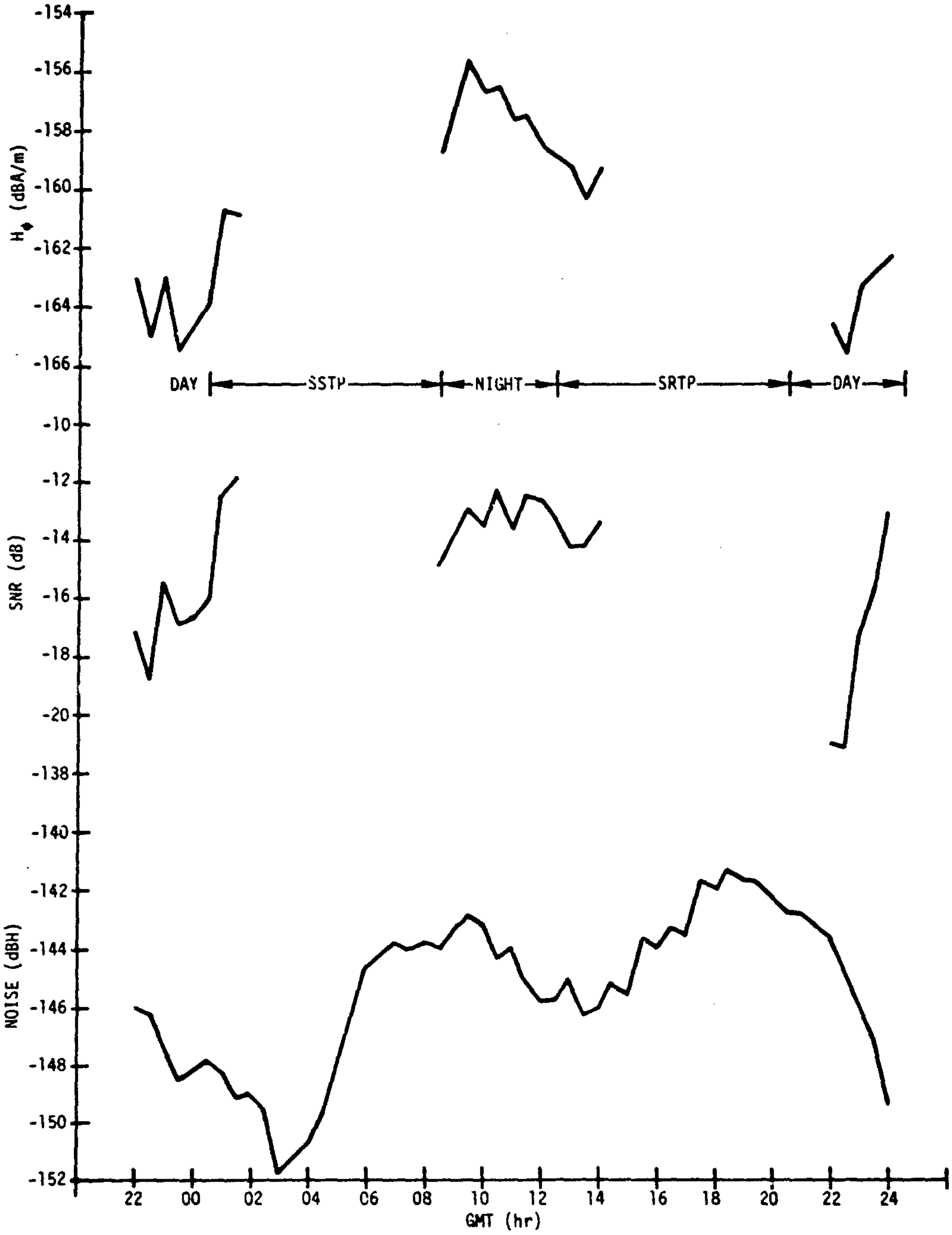

Figure C-14. Western-Pacific-Area Submarine Data Versus GMT (ψ = 291 deg), 14 October 1977

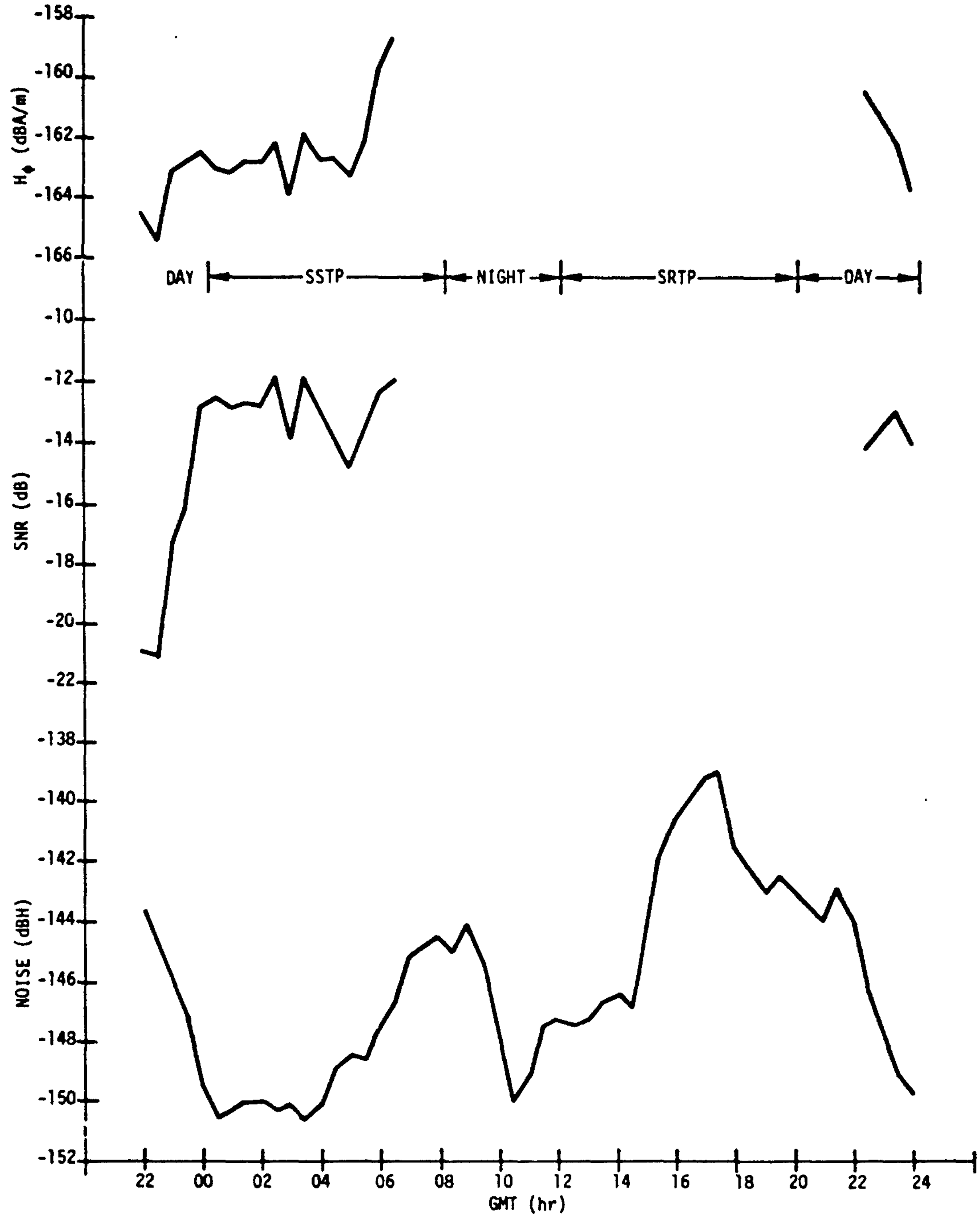

Figure C-15. Western-Pacific-Area Submarine Data Versus GMT (ψ = 291 deg), 15 October 1977

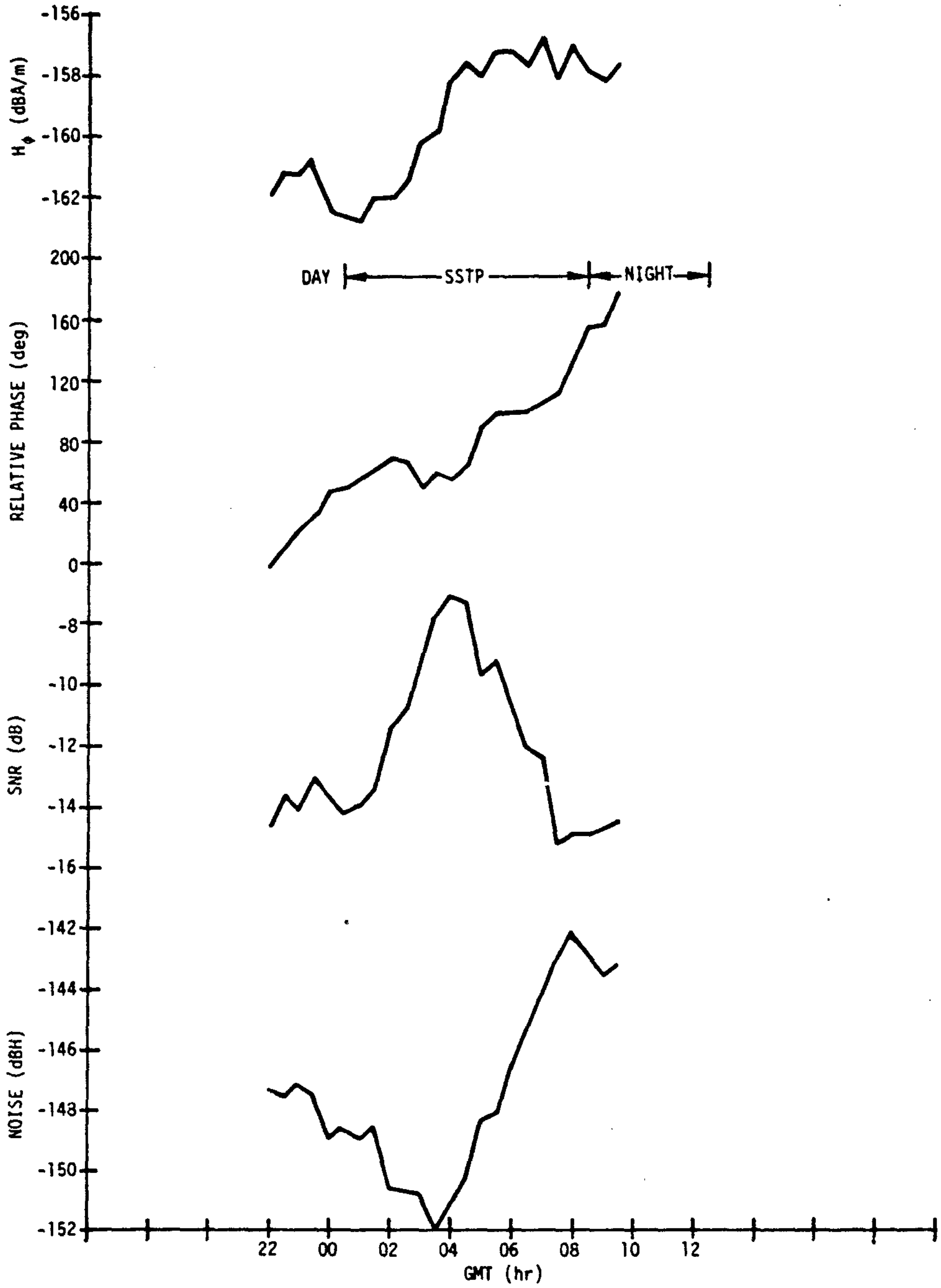

Figure C-16. Western-Pacific-Area Submarine Data Versus GMT (ψ = 291 deg), 17 October 1977

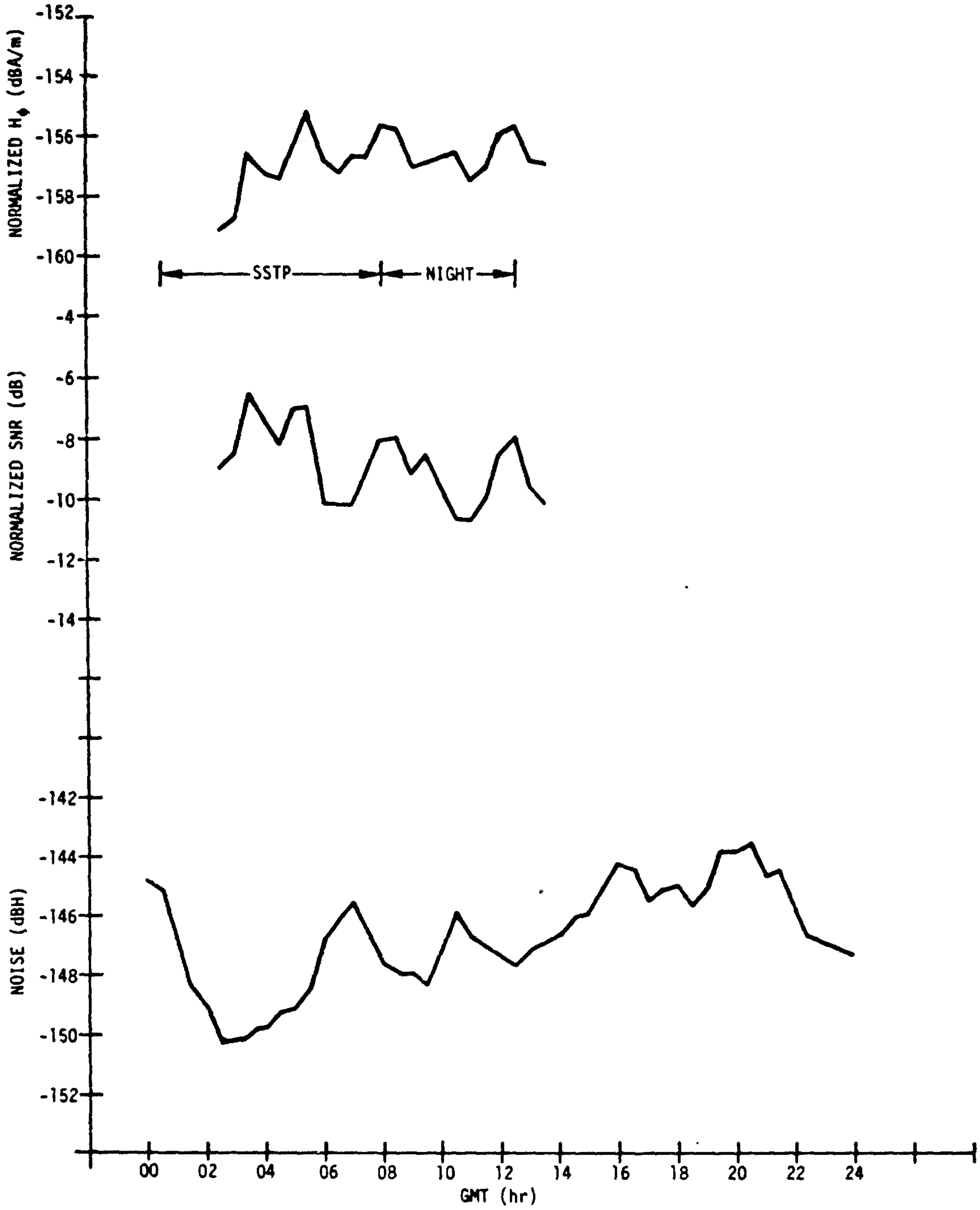

Figure C-17. Western-Pacific-Area Submarine Data Versus GMT (ψ = 21 deg), 22 October 1977

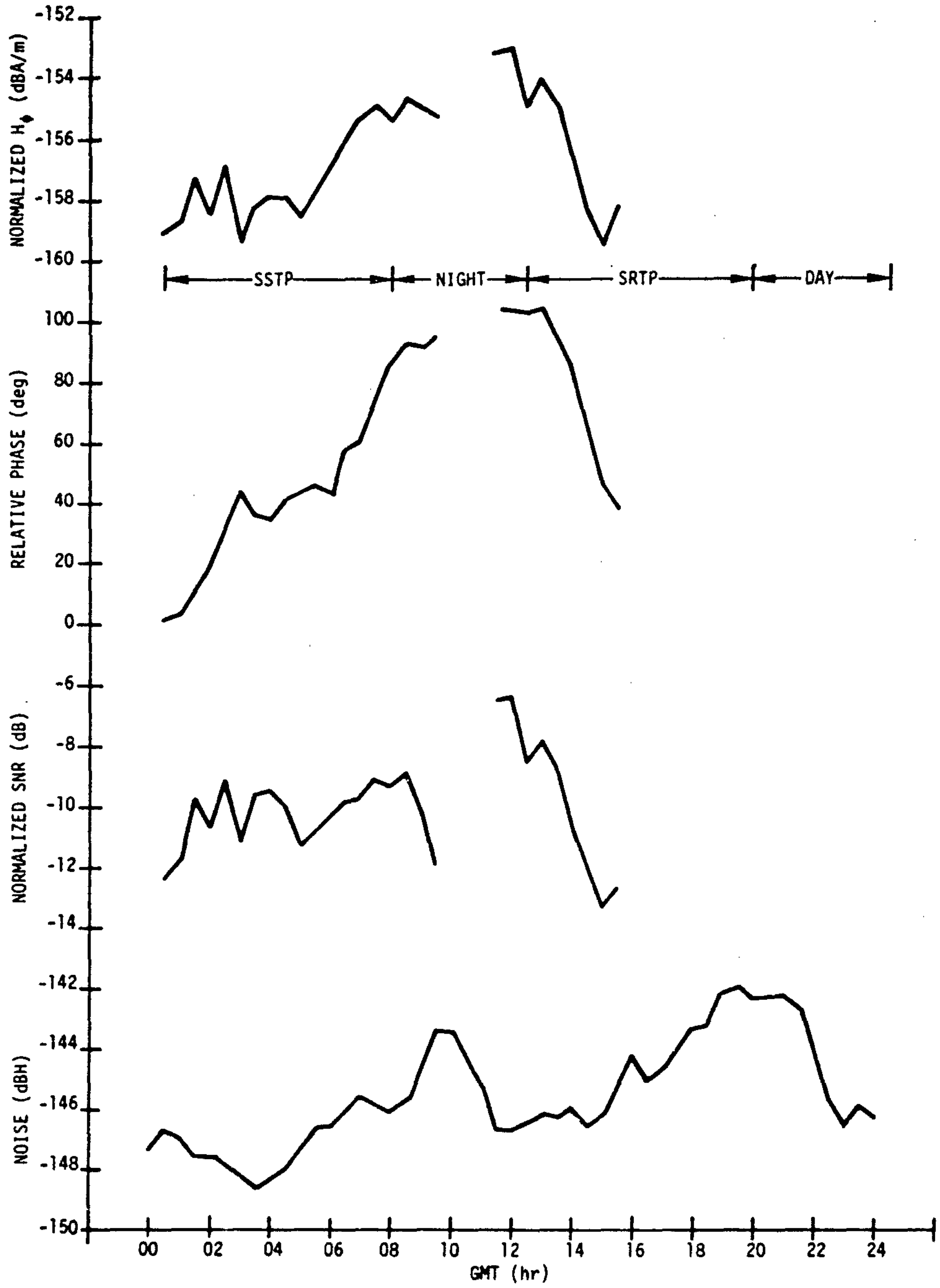

Figure C-18. Western-Pacific-Area Submarine Data Versus GMT (ψ = 21 deg), 23 October 1977

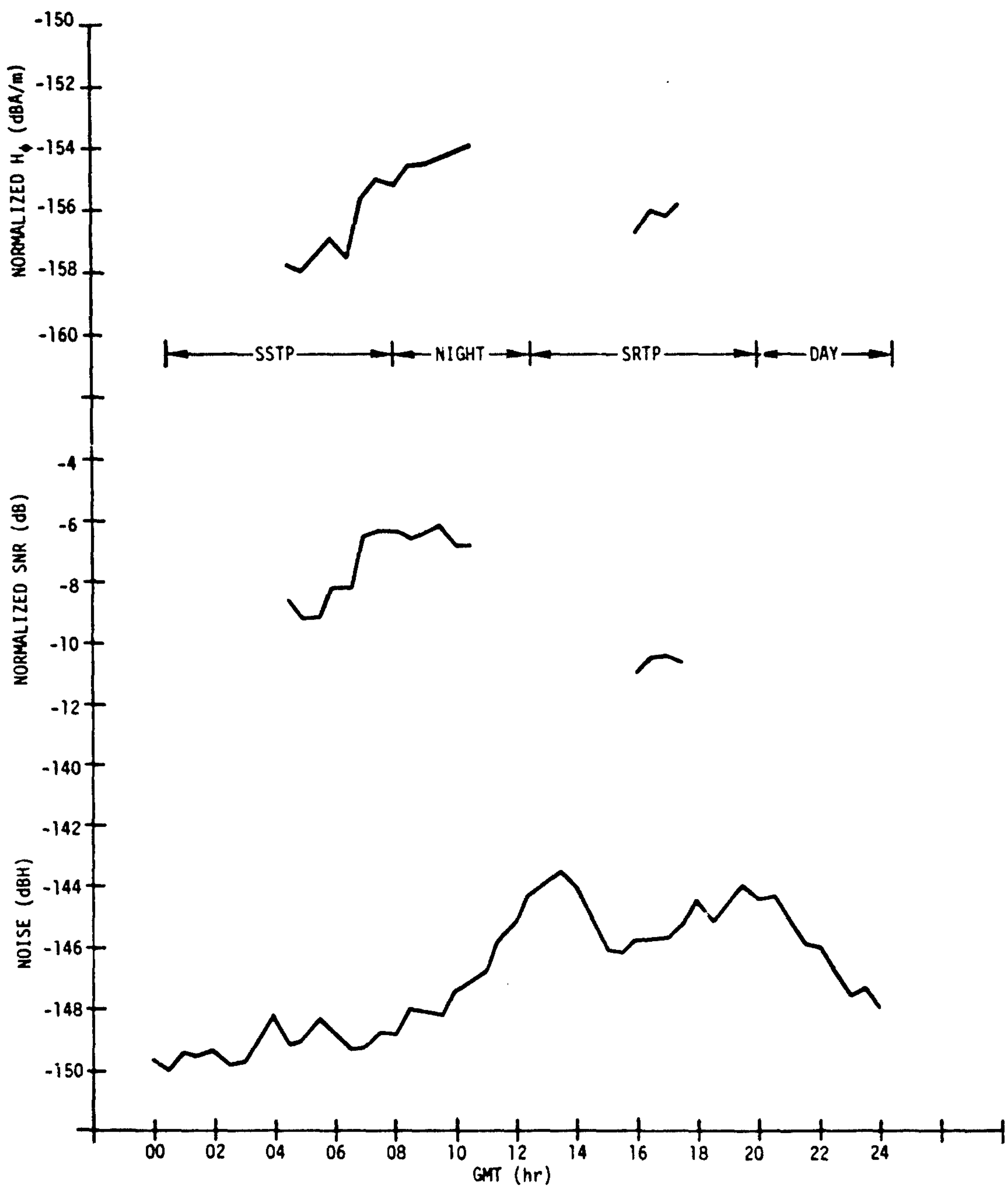

Figure C-19. Western-Pacific-Area Submarine Data Versus GMT (ψ = 21 deg), 25 October 1977

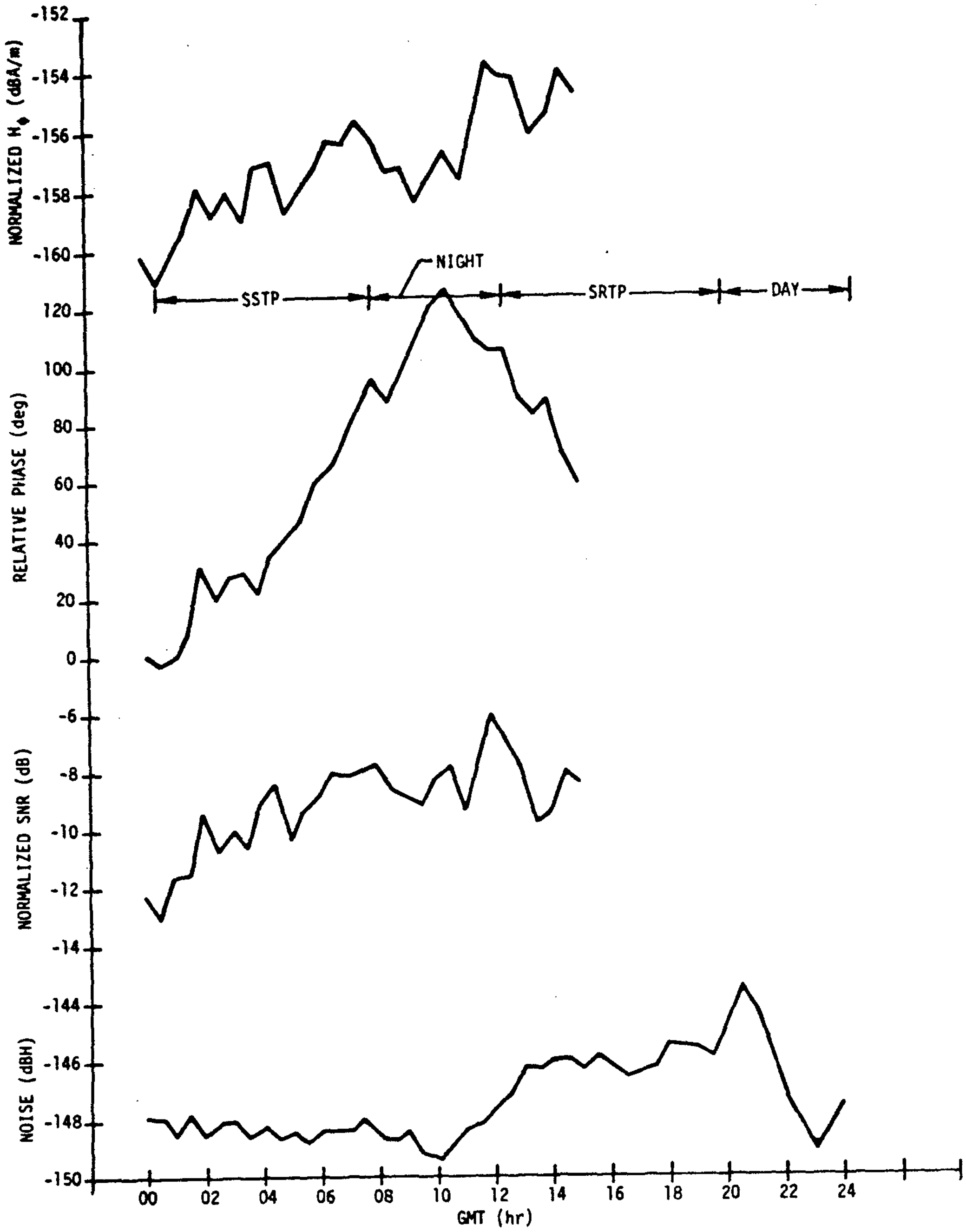

Figure C-20. Western-Pacific-Area Submarine Data Versus GMT (ψ = 21 deg), 26 October 1977

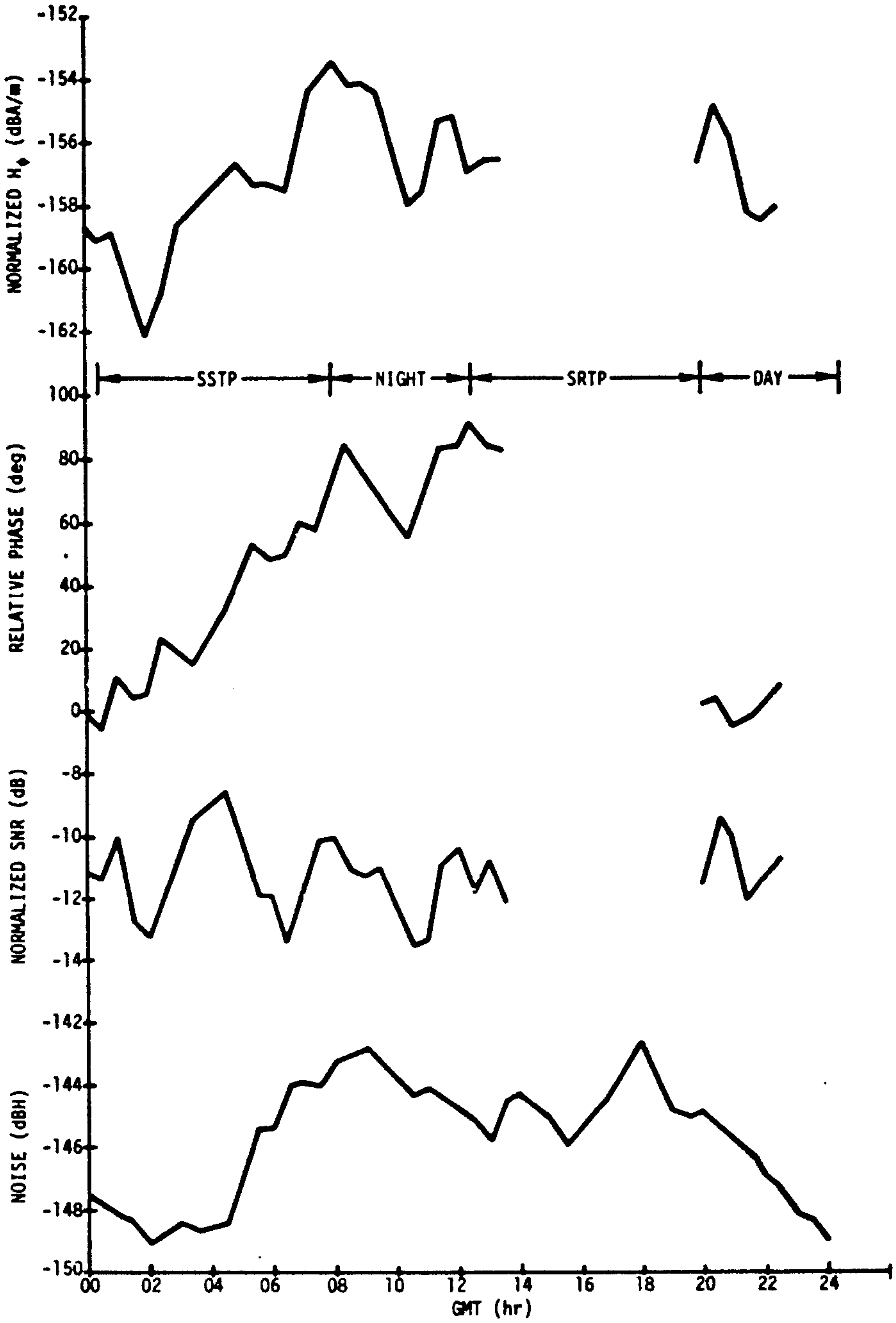

Figure C-21. Western-Pacific-Area Submarine Data Versus GMT (ψ = 21 deg), 27 October 1977

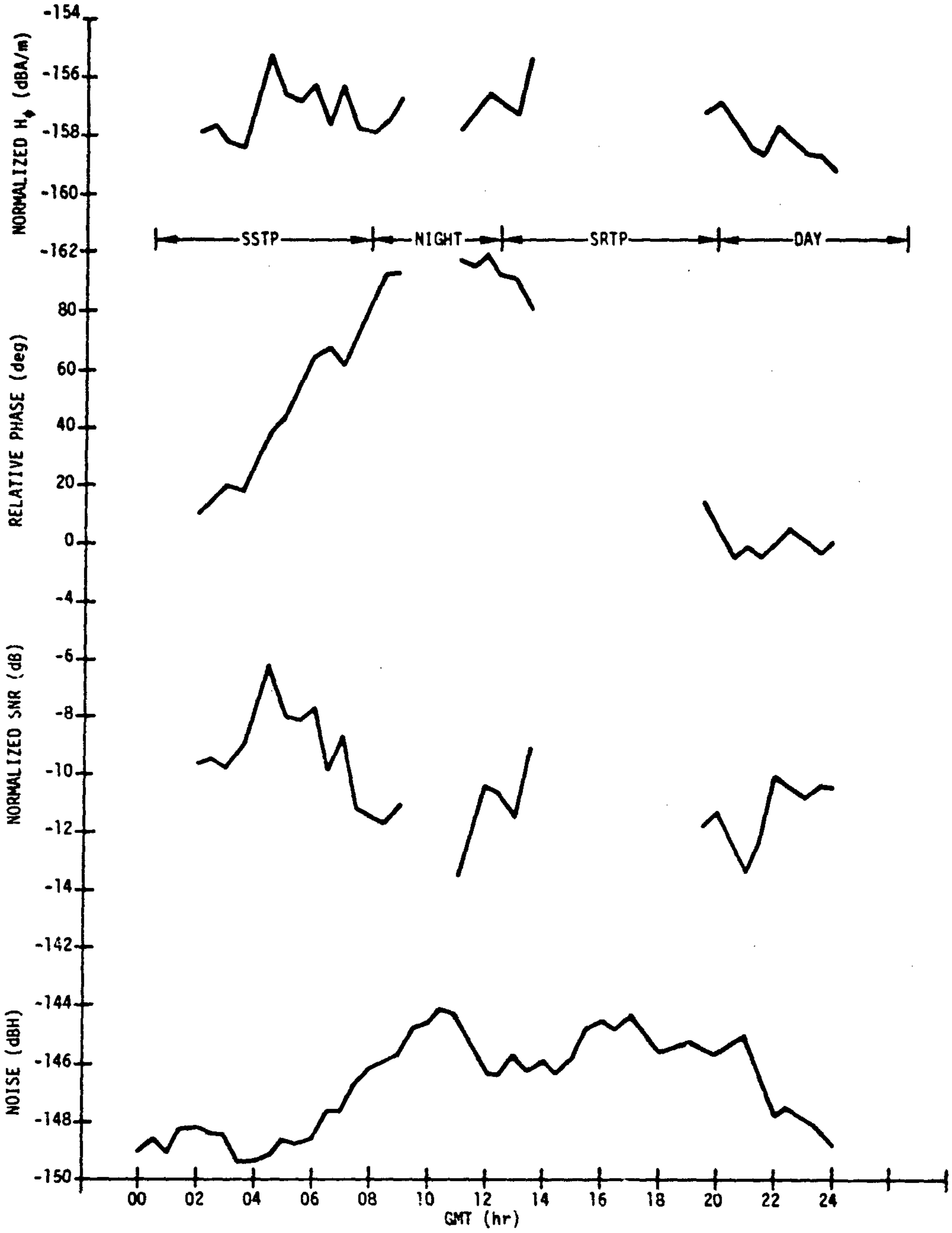

Figure C-22. Western-Pacific-Area Submarine Data Versus GMT (ψ = 21 deg), 28 October 1977

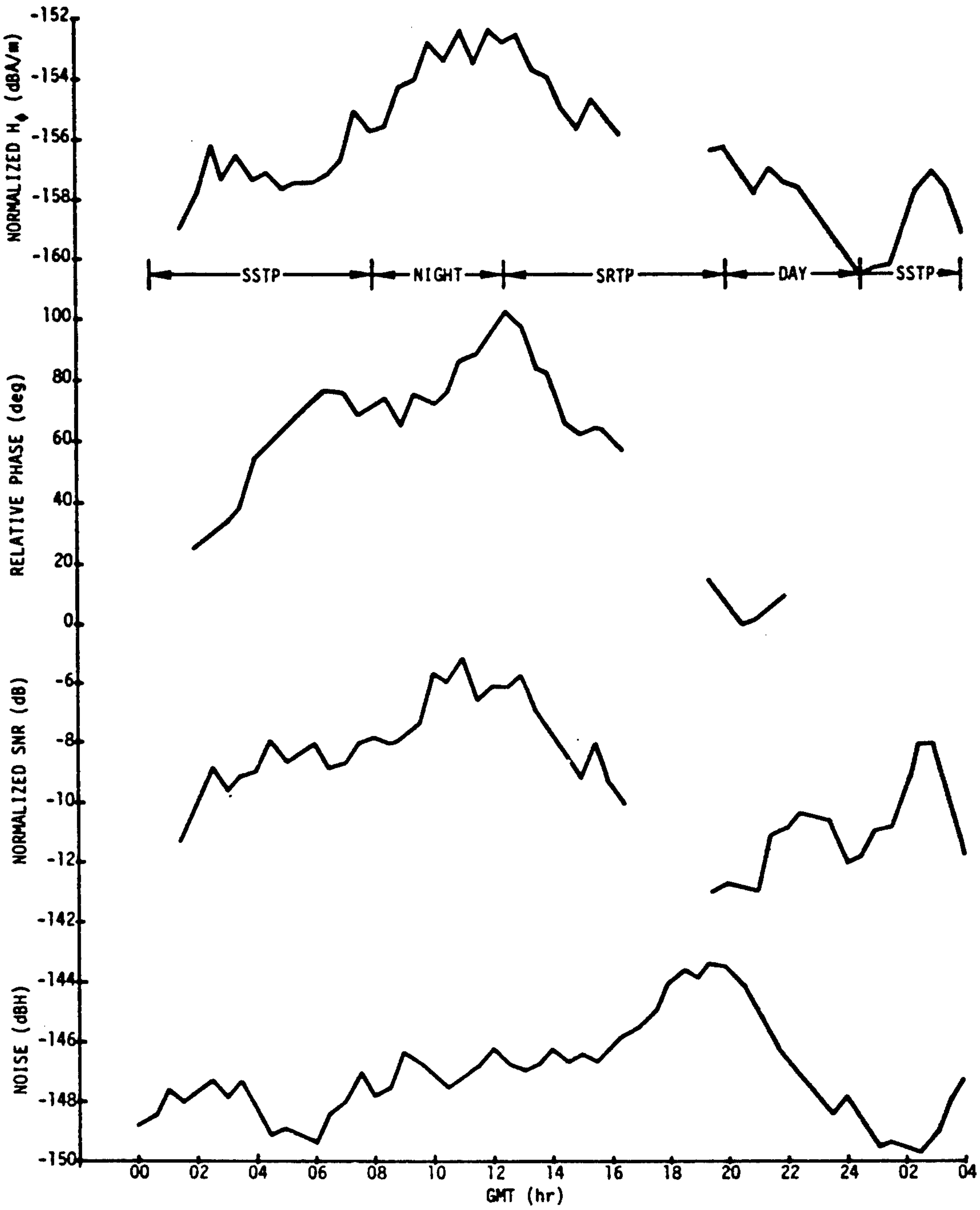

Figure C-23. Western-Pacific-Area Submarine Data Versus GMT (ψ = 21 deg), 29 and 30 October 1977

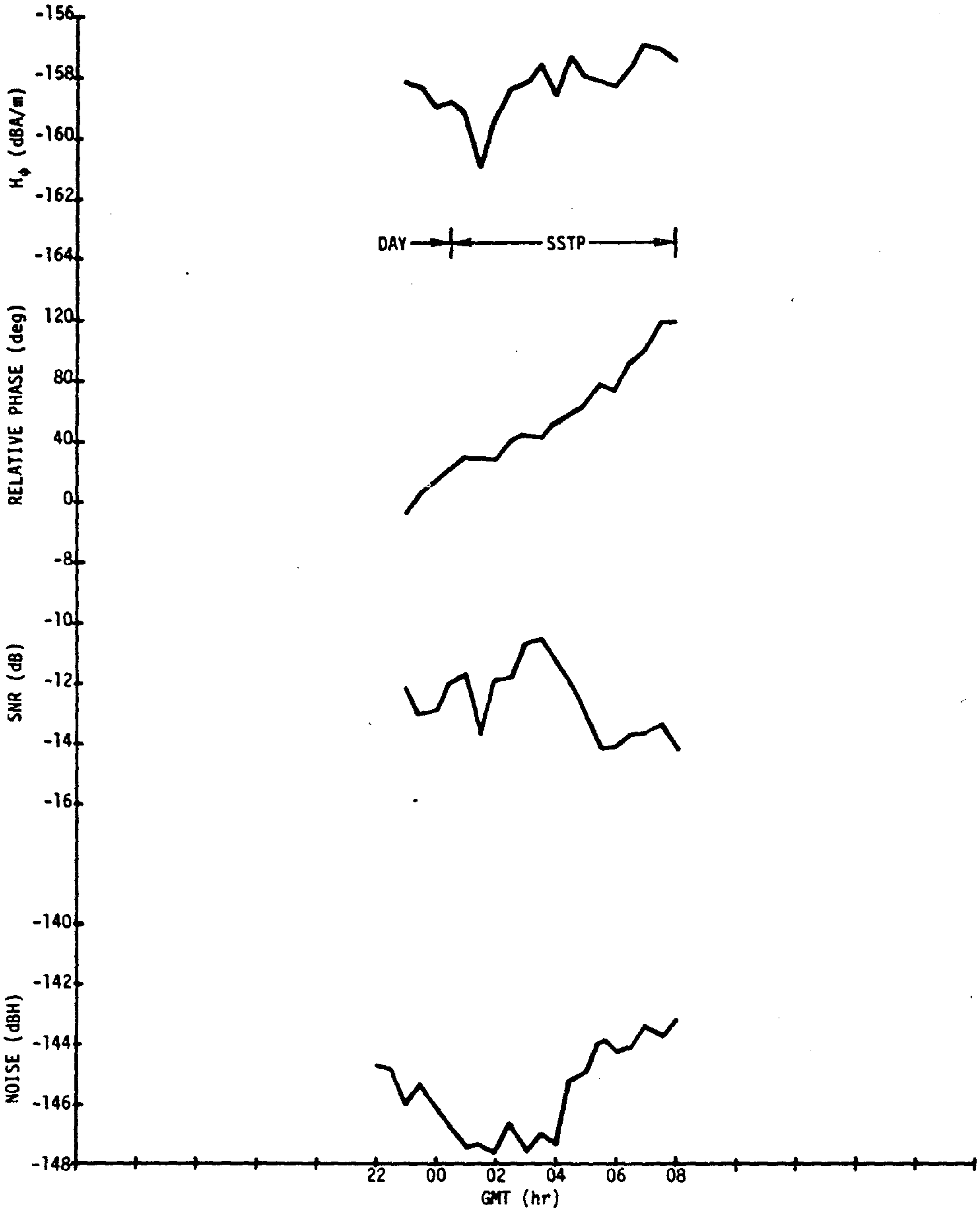

Figure C-24. Western-Pacific-Area Submarine Data Versus GMT (ψ = 291 deg), 3 and 4 November 1977

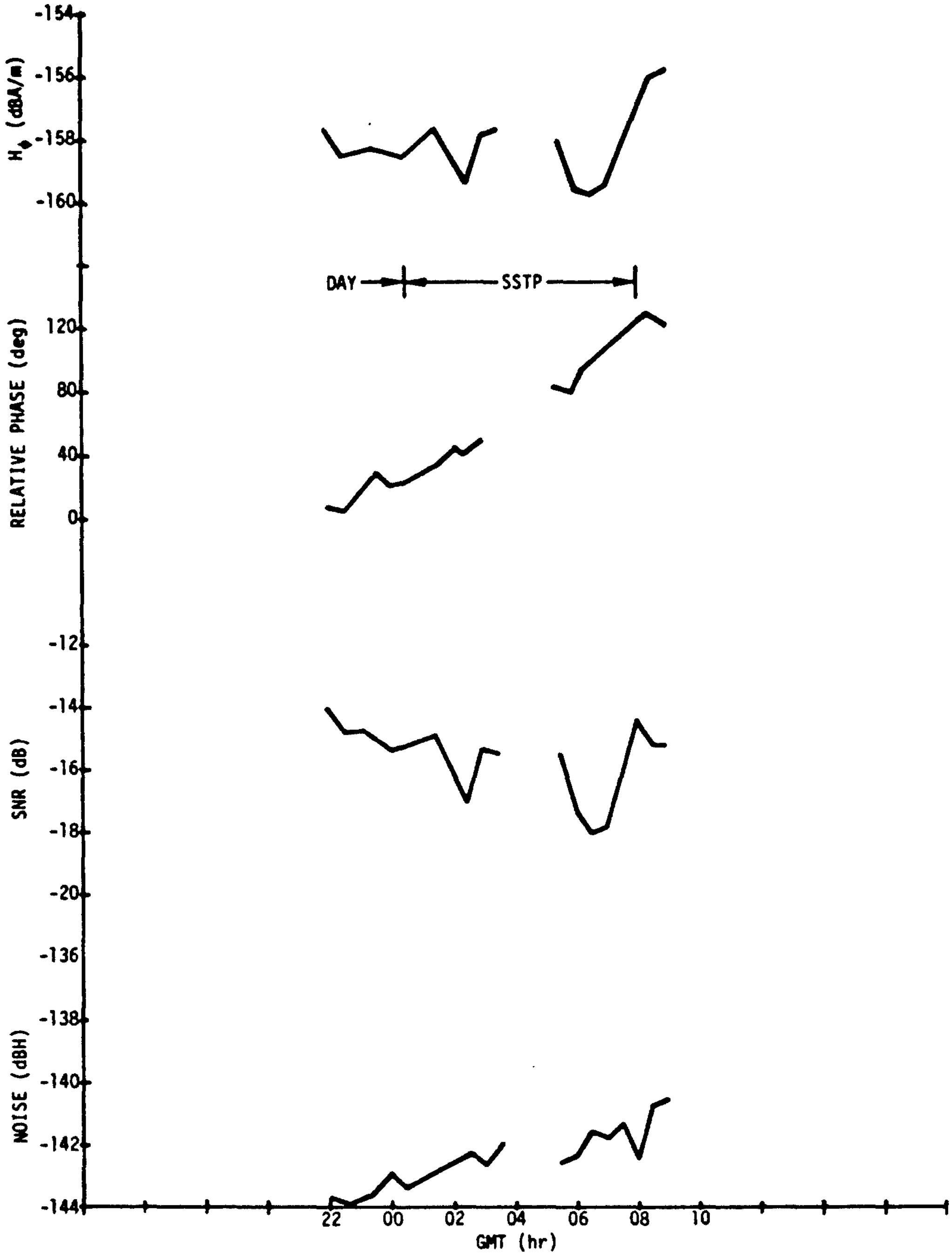

Figure C-25. Western-Pacific-Area Submarine Data Versus GMT (ψ = 291 deg), 4 and 5 November 1977

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