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Comparisons of Surface and Borehole Broadband Ambient Seismic Noise at IRIS Station RAR: Raratonga, Cook Islands

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This report addresses reduction of ambient broadband (.01 - 10 Hz) seismic noise achieved by a 100 m deep borehole deployment on a small oceanic island, Raratonga in the Cook Islands, relative to simultaneously recorded surface levels. Between .5 - 5 Hz, no difference was observed between surface and borehole noise levels. Significant noise reduction is achieved by the borehole seismometer for horizontal components at frequencies below .5 Hz, but these vary with time of day. A noise disturbance is observed during the day at RAR that can raise long-period horizontal surface noise levels 20 dB above quiet periods. During this daily noisy period, borehole horizontal noise in the borehole is about 20 dB less than surface levels. Away from this noise disturbance, horizontal long-period noise reduction varies from 0 to about 12 dB between .01 - .05 Hz. On the average there is no reduction in long-period noise on the vertical component. Above about 5 Hz, a moderate noise reduction (3-6 dB) is observed on the average for both vertical and horizontal components. These results are similar to comparisons of surface and borehole noise in a continental setting. While a borehole deployment is helpful in reducing seismic noise in some frequency bands, it does not mitigate the inherently noisy conditions associated with a small oceanic island.

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Comparisons of surface and borehole broadband ambient seismic noise at IRIS station RAR: Raratonga, Cook Islands

Summary

We address the broadband noise reduction achieved by a 100 m deep borehole deployment on a small oceanic island, Raratonga in the Cook Islands, relative to simultaneously recorded surface levels. Results show that significant noise reduction achieved by the borehole seismometer is largely limited to horizontal components at frequencies below .05 Hz. Above about 5 Hz, a moderate noise reduction (3-6 dB) is observed on the average for both vertical and horizontal components. Between .05 - 5 Hz, no difference was observed between surface and borehole noise levels. These results are similar to comparisons of surface and borehole noise in a continental setting. While a borehole deployment is helpful in reducing seismic noise in some frequency bands, it does not mitigate the inherently noisy conditions associated with a small oceanic island.

Background

Deployments of seismometers in boreholes has been observed reduce ambient seismic noise levels under some conditions in some frequency bands. One example is the network of Seismic Research Observatory (SRO) stations deployed by the U.S. Geological Survey for ARPA in the 1970's. SRO stations had a general bandwidth from .01 - 10 Hz; deployments were in 100 m deep boreholes to reduce long-period wind-induced noise seen on horizontal components for surface vault deployments. Peterson et al (1976) reported a reduction of about 10 dB in noise power spectral density between .01 - .1 Hz for horizontal components in a 100m deep borehole versus a 15 m deep borehole for 50 km/hour wind conditions at the Albuquerque Seismological Laboratory.

Berger et al (1988), Gurrola et al (1990), and Given (1990) reported on lower noise observed in 100-m deep boreholes compared to surface noise at frequencies above 1 Hz. These studies were done at stations in continental interiors: eastern Kazakhstan, the western US, and parts of Russia and central Asia. Gurrola et al (1990) in particular summarized many noise observations between 1-80 Hz recorded by high frequency sensors, the Teledyne Geotech GS-13 surface seismometer and the Teledyne Geotech KS54100 borehole seismometer, where an anemometer system simultaneously recorded wind speed. They found that borehole noise was generally less than surface noise above 10 Hz by 3-15 dB. The largest differences occurred at frequencies above 20 Hz. Gurrola et al (1990) found that seismic noise did not significantly correlate with wind speed for frequencies from 1-10 Hz, and that surface and borehole noise levels in this band were similar. Gurrola et al (1990)'s study was done at very quiet stations; absolute noise levels below the reference low noise models (generally quoted at -168 dB relative to $(1 m/s^2)^2/Hz$ above 2 Hz) were observed at some of them. Some of the stations used by Given (1990) showed noise reductions of up to 20 dB achieved by using a borehole seismometer, with these large values again occurring well above 10 Hz.

Recently, IRIS (the Incorporated Research Institutions for Seismology) has promoted the use of very broadband seismometers in boreholes as a noise reduction technique in the Global Seismographic Network (GSN), emphasizing deployments on oceanic islands. In early 1992, an experiment began where a Teledyne Geotech KS36000i seismometer in a 100-m deep cased borehole was recorded continuously and simultaneously with a set of Streckeisen STS-1 seismometers in a nearby surface vault on Raratonga, a small (67 km^2) island in the Cook Islands in the south Pacific. Butler and Hutt (1992) described the first results of this noise experiment. In this report, we corroborate and expand on their results, emphasizing results at high frequencies and comparisons with continental stations.

Analysis of Noise Reduction Achieved at IRIS GSN station RAR

Project IDA at Scripps Institution of Oceanography has run a LaCoste gravimeter station on Raratonga since 1976. Figure 1 shows the building that houses the IDA instrument and where IRIS STS-1 seismometers where installed in 1992. Seismometers are located on piers inside the building. The RAR station is located less than one mile inland in a steep ravine cut by Lakuvaine stream. The back wall of the building is against one side of the ravine although there is enough room for a person to walk between (Don Miller, personal communication).

Figure 2 shows time series of a typical five-day period recorded by the IRIS station at RAR on the borehole (top) and surface (bottom) sensors. Traces shown are from the VLP (.1 sample per second) channels and instrument responses have not been removed. Borehole sensors do not show Earth tides due to a one-pole high-pass filter with a corner period of 1500 s. Vertical scales differ for the two instruments, but the three components from each seismometer are shown on the same scale so that horizontal amplitudes can be compared directly to the vertical. The x axis shows hour-of-day in GMT. Most notable in this plot is the large daily disturbance seen on the horizontal surface seismometers (traces VHV and VHW). The onset of this characteristic signal generally occurs between 18:30 - 19:30 GMT (7:30 - 8:30 am local time) and persists between 4.5 - 5.5 hours. It is more pronounced on the north than on the east channel. Although only one five-day period is shown here, examination of many weeks of RAR data shows that this signal is a persistent daily feature. Note that this disturbance is not seen on the borehole channels, where little diurnal variation is observed. It was discovered after installation that the KS36000i seismometer package was oriented N25°E, N115°E; this orientation is not corrected for in Figure 2, but in the comparison of power spectral estimates of noise discussed below, the borehole horizontal components were rotated to true North and East such that they are directly comparable with the surface horizontal components.

Figures 3 - 14 show power spectral estimates between frequencies of .01 - 10 Hz calculated every two hours from the broadband (VBB) channels of IRIS RAR data for the twenty-four hour period beginning 1992:085:00:00 GMT. A simple band-averaging moving window method outlined in Given (1990) was used where length of the moving time window is 500 seconds. Time series were visually inspected for obvious earthquake signals; only one sample had to be shifted by 10 min to avoid an earthquake. Instrument responses were calculated from SEED data provided by the IRIS Data Management Center and they have been removed from the power spectra. Spectral levels are shown in acceleration, in decibels relative to 1 $(m/s^2)^2/Hz$. Spectral levels observed on the surface Streckeisen seismometers are solid lines and those from the KS36000i borehole seismometer are dashed. A quick look at these figures shows that noise reduction on the borehole seismometer, when observed, is limited to two frequency bands: frequencies lower than .05 Hz and frequencies above 3 Hz.

Noise Reduction at Low Frequencies (Below .05 Hz)

Below .05 Hz, noise reduction achieved by the borehole sensors can vary from 0 dB to 25 dB and is mainly seen on the horizontal components. Noise reduction on the horizontal borehole components is very strongly dependent on the time of day of the observation. For example, the noise sample at 06:00 GMT (Figure 6) shows no noise reduction by the borehole sensors at low frequencies, whereas the noise sample at 20:00 GMT (Figure 13) shows up to 25 dB of noise reduction relative to the surface horizontal sensors at .01 Hz. Noise reductions of 20 dB or more on the horizontal borehole sensors can be explained by the large daily noise disturbance seen in the time series in Figure 1. Away from this noise pulse, say from 02:00 - 18:00 GMT, noise reductions by the horizontal borehole sensors are more moderate, varying from 0 to about 12 dB.

Figure 15 shows the average difference in decibels of surface noise power minus borehole noise power from .01 - 1 Hz for the twelve noise samples taken over the 24-hour period. Dashed lines show the maximum and minimum differences found at each frequency point. From .05 - 1 Hz, noise levels observed on the borehole and surface sensors are the same on all components at all times. Below .05 Hz, the borehole noise on average is the same as surface noise for the vertical component. Borehole noise is on the average lower than surface noise on the horizontal components below .05 Hz, reaching an average difference of 12-13 dB between .01-.02 Hz (50-100 seconds). If the four noise samples taken during the noise disturbance (at 18:10, 20:00, 22:00 and 00:00 GMT) are excluded from the average, the largest average noise reduction observed is just under 10 dB (Figure 16).

Comparison with continental results. These results are essentially the same as those observed by Peterson et al (1976) at a continental site (Albuquerque); where horizontal noise reductions on the order of 10 dB for a 100-m deep borehole were observed, comparable with the RAR results away from the noisy time period. Peterson et al (1976) also reported a noise reduction on the vertical component of 3-5 dB from .1 - .01 Hz under 50 km/hour wind conditions. Similarly, values of noise reduction by the borehole vertical sensor at RAR of around 5 dB have been observed at times (Figures 15,16), although not for frequencies above .5 Hz.

Characteristic diurnal noise variations affecting horizontal components at long periods are often observed at continental sites where seismometers are contained in a building or shallow surface vault. Figures 17-18 show examples of five-day long time series for IRIS/IDA stations PFO (Pinon Flat, California) and RPN (Easter Island, Chile) from STS-1 VLP channels. Amplitude scales differ between figures, but horizontal channels are plotted with the same scale as the vertical for each station so that horizontal ground motion can be compared with the size of the vertical Earth tides. At both stations the horizontal noise disturbance begins in the early morning and is thought to be caused by the response of the ground to daily warming. This can manifest itself in different ways due to unique conditions at each station, such as the orientation of the vault or the range of temperature variation. Daily winds can also contribute to a regular noise effect. The top of the vault at Pinon Flat is about 2 feet underground in weathering granite and entered by a hatch door at the surface. The vault at Easter Island is a concrete room built back into a low hill formed by a weathering lava flow and mounded over with earth; the door to the vault is exposed and faces southeast (the direction of sunrise and prevailing winds).

The PFO data is particularly instructive because solar radiation (from a photo cell) and wind (from an anemometer system) are continuously logged with the seismic data. Inflections are seen on the E-W seismic component that coincide exactly with the beginning and end of daylight; these can be interpreted as tilts caused by a sudden change in temperature of the ground around the vault. The temperature effects of sunrise and sunset are abrupt at PFO because the vault is in the shadow of mountain ranges to the east and west that block the sun when it is still substantially above the horizon. Clouds that occurred during the afternoons of the first and third days (see Figure 17, fourth trace) are also seen to have some effect on very long-period seismic noise, either by changing the ground temperature or by pressure-loading the ground from convective air motions. Increased wind speeds during the last day shown in Figure 17 are correlated with higher seismic noise on the horizontal components (see traces 3 and 5), but this noise is much higher frequency than that associated with daily temperature variation or cloud cover.

Noise Reduction at High Frequencies (Above 5 Hz)

Figures 3 - 14 show a small amount noise reduction above 5 Hz by the borehole seismometer on all components at certain times of the day. Figure 19 shows the average difference in decibels of borehole noise power minus surface noise power on a linear scale from 1 to 9 Hz. The average was formed from the 12 samples shown in Figures 3-14 and thus this plot does not address a time-of-day variation. The maximum and minimum differences at selected frequencies are shown as asterisks on Figure 19. The largest average difference seen on the vertical component is about 6 dB achieved at 7 Hz; at times no difference is seen between noise levels on the borehole and surface sensors while at other times noise reduction can reach 10 dB. Vertical component noise reduction by the borehole is not significant below 4 Hz. Average high frequency noise reduction for horizontal components is similar to the vertical component.

Figures 3-14 give an indication of the time-of-day variation in noise reduction by the borehole at high frequencies, as well as the time-of-day variation in absolute noise levels. Noise reductions of 5 dB or more on the vertical appear to be correlated with the noisy daytime period from 18:00 - 00:00 GMT. No noise reduction is achieved by the borehole seismometer from 08:00 GMT - 16:00 GMT. *Absolute* noise power levels are also higher during the noisy daytime period, for example, noise at 5 Hz is about 10 dB higher at 00:00 GMT than at 12:00 GMT for both borehole and surface sensors.

Comparison with continental results. The RAR results fall within the range of observations of other borehole versus surface noise comparisons from 1 - 10 Hz. Given (1990) found that noise reductions began to be significant (5 dB) at about 4 Hz and reached their maxima well over 10 Hz. Gurrola et al (1990) found that borehole and surface noise was comparable from 3-10 Hz for generally quiet stations far from cultural noise.

Absolute Noise Levels at RAR

Figure 20 compares the absolute noise power observed by the borehole seismometer at RAR during a quiet time studied, 06:00 GMT on day 1992:085, with an average of night-time noise observed at a continental station over a one-week period (IRIS/IDA station AAK). The RAR noise power spectral density shown here agrees generally with typical RAR noise during quiet periods (Hoffman and Peterson, ASL Station Book, unpublished). Station AAK has moderately low noise at 1 Hz due to its remoteness from culture and location in a rock tunnel, and has low noise at around the microseism frequency due to its location in central Asia far from oceans (Given, 1990; Given and Fels, 1993). The RAR noise power spectral density is 30-40 dB above average noise observed at AAK in the body wave band (.1 - 1 Hz), and 5-15 dB above noise in the frequency band relevant for regional detection seismology (2-10 Hz) on all channels. In general however we note that the Streckeisen seismometer at AAK was not designed for operation above a few Hz; high-frequency noise at this station is best studied using data from co-located GS-13 instruments.

Conclusions and Recommendations

The borehole seismometer at RAR achieves some reduction in horizontal component noise at long periods, although the values of 20 dB reported by Butler and Hutt (1993) are mostly related to a daily noise disturbance affecting the horizontal surface seismometers. Away from this noise disturbance, horizontal long-period noise reduction varies from 0 to about 12 dB between .01 - .05 Hz. On the average there is no reduction in long-period noise on the vertical component. These same effects are seen in continental comparisons of surface versus borehole noise, where lower horizontal long-period noise in the borehole is due mainly to the elimination of wind and surface tilt. This noise reduction is significant for some seismological studies; for example, routine global CMT (centroid moment-tensor) determinations for moderate-sized earthquakes will be improved by additional long-period surface wave data on horizontal components below .05 Hz, as will studies of whole-Earth structure, particularly where oceanic stations can provide badly needed path coverage.

Results from the Raratonga experiment and other studies show that from .05 - 1 Hz, a borehole seismometer provides no noise reduction over surface levels in most cases. Above 4 Hz, a modest (3-6 dB) average noise reduction is seen at RAR. Thus for teleseisms with a dominant frequency near 1 Hz, it is unlikely that borehole deployments on oceanic islands will significantly improve detection or location capability beyond that achievable by a surface sensor at the same location. Studies of local and regional events may benefit by the moderately lower noise levels observed in a borehole over 4-5 Hz. Frequencies above 10 Hz are outside the band of the RAR instruments.

Although results are drawn from limited data, we have confirmed that the noise characteristics at RAR discussed here are a very stable feature of the station. Absolute noise levels seen during the study period agree with other studies, as well as those characterizing the station in the ASL Station Book.

Borehole deployments on oceanic islands achieve noise reduction over surface instruments for the same reasons that borehole deployments do on land. However, borehole deployments on oceanic islands provide no noise reduction in a large part of the seismic band, and they do not mitigate the inherently noisy conditions of the island environment. The price of a seismographic station on an oceanic island, in terms of site preparation and instrument cost, is usually increased by the choice of a borehole seismometer, particularly when drilling equipment must be brought by ship to a remote location.

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Figure Captions

Figure 1. The recording building at Raratonga, which also houses the Streckeisen STS-1 seismometers and LaCoste gravimeter.

Figure 2. Five days of seismic data from the IRIS station RAR. Top three traces are from the borehole sensor, lower three from STS-1 surface sensors. The time axis shows hours in GMT. The amplitude scale is arbitrary but is the same for the top three traces and the lower three traces, so that horizontal amplitudes can be compared with the vertical for each sensor. Earth tides are apparent in on the surface vertical sensor but not seen on the borehole vertical sensor due to a difference in instrument response. While borehole channels at RAR show no diurnal variation, a large daily noise disturbance is apparent on the horizontal surface sensors. This disturbance is a very stable feature of the station.

Figure 3-14. Power spectral densities of three component ambient seismic noise from .01 Hz to 9 Hz, taken every two hours in a 24-hour period. Units are decibels relative to 1 $(m/s^2)^2/Hz$. Noise levels from the surface sensors are solid lines; those from the borehole sensors are dashed. Time (in GMT) of the noise sample is shown on the plots. Instrument responses have been removed.

Figure 15. Average difference in decibels in surface versus borehole noise from .01 to 1 Hz. Positive values indicate larger surface noise. Averages are formed from twelve individual samples taken at 2-hour intervals. Dashed lines denote maximum and minimum differences observed at a given frequency from any of the twelve noise samples. Lower noise in the borehole is limited to horizontal components is significant only below .5 Hz.

Figure 16. Same as Figure 15 but with four of the noise samples that occurred during the daily noise disturbance eliminated from the average. Away from the noisy period, horizontal-component noise observed in the borehole is still quieter on the average than surface noise below .5 Hz by about 6-10 dB.

Figure 17. Five days of seismic data from the continental IRIS station PFO, where STS-1 seismometers are deployed in a vault 2 m below the surface in weathered granite. The top three traces have the same amplitude scale. The 4th and 5th traces are solar radiation (roughly from 0 to 950 W/m^2) and wind speed (roughly from 0 to 7 m/s) respectively. The horizontal components, most notably the E-W, show a large twice-per-day effect that correlates with daily warming of the ground around the vault. Both horizontal components show an increase in low-frequency seismic noise with wind speed.

Figure 18. Five days of seismic data from the IRIS station RPN on Easter Island, where STS-1 seismometers are deployed in a surface vault dug back into a weathering lava flow. RPN shows an increase in horizontal component noise during daytime similar in many respects to RAR.

Figure 19. The average difference in decibels in surface versus borehole noise shown on a linear frequency scale between 1 and 9 Hz. Positive values indicate larger surface noise. Averages are formed from the twelve individual samples taken at 2-hour intervals. Asterisks denote the maximum and minimum differences observed at a given frequency from any of the twelve noise samples.

Figure 20. Power spectral densities of ambient seismic noise at IRIS station RAR (upper curve) and IRIS station AAK (lower curve) in central Asia, in decibels relative to 1 $(m/s^2)^2/Hz$.

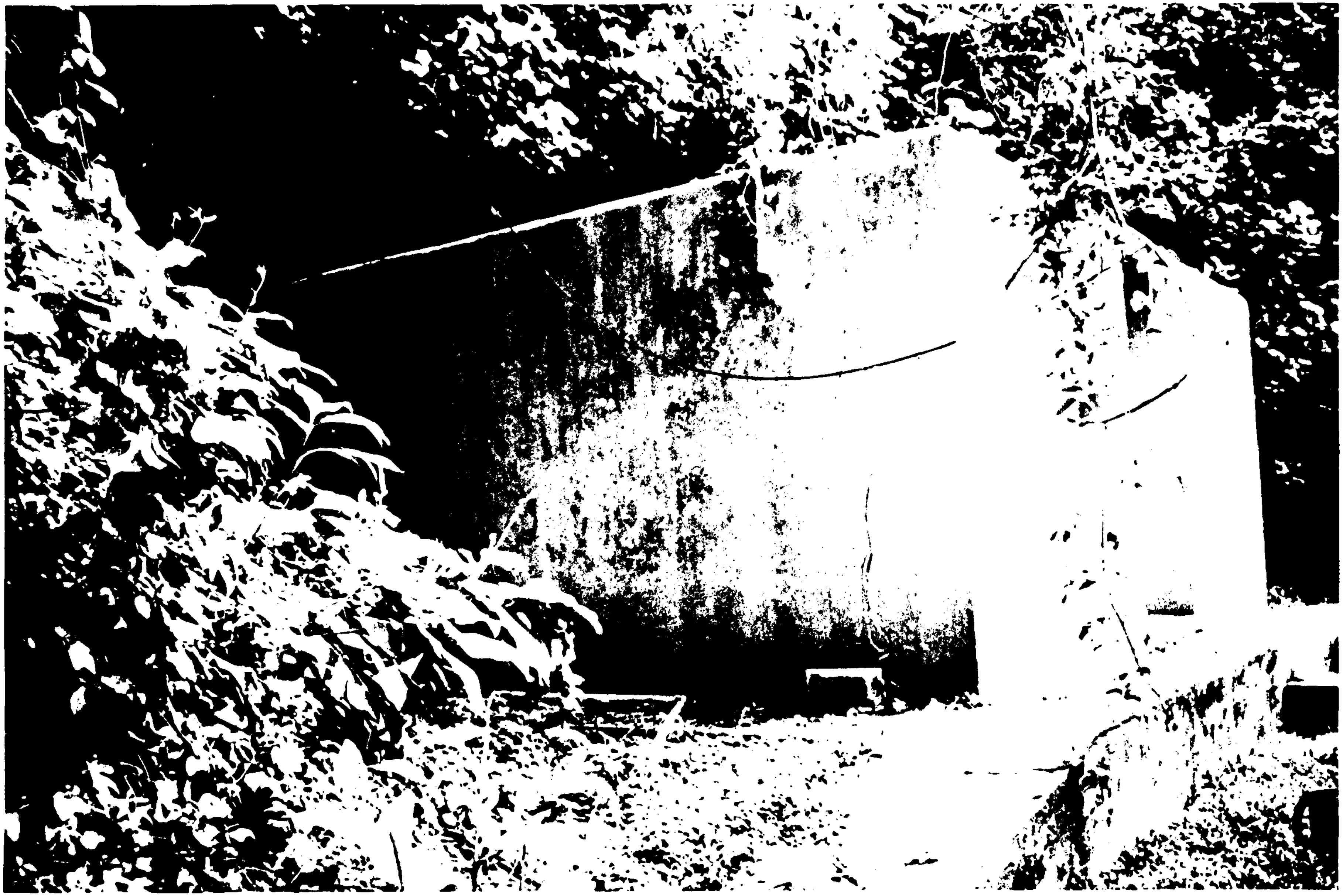
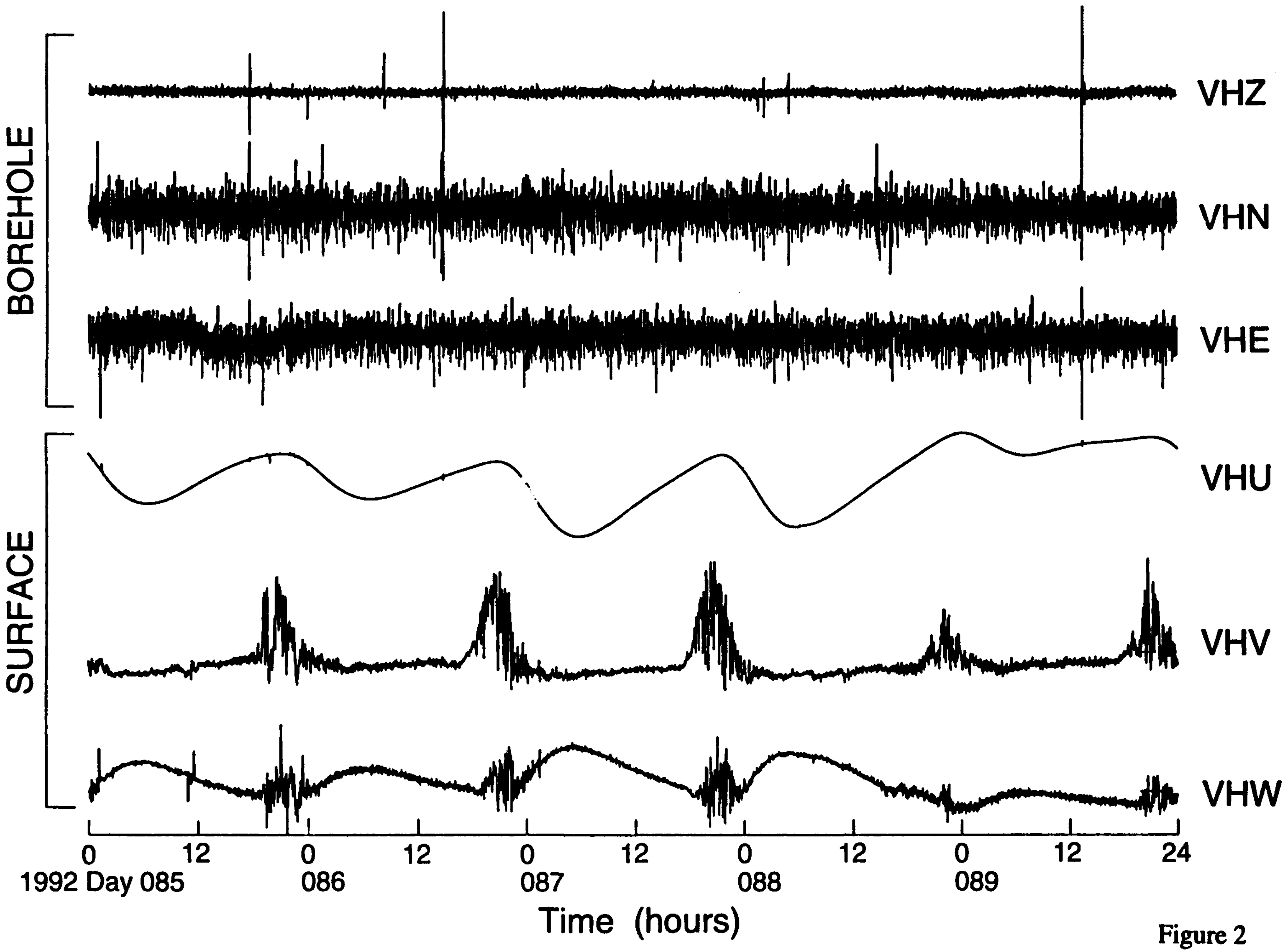


Figure 1

Five Days RAR KS36000i and STS-1 Data <1992:085-089>



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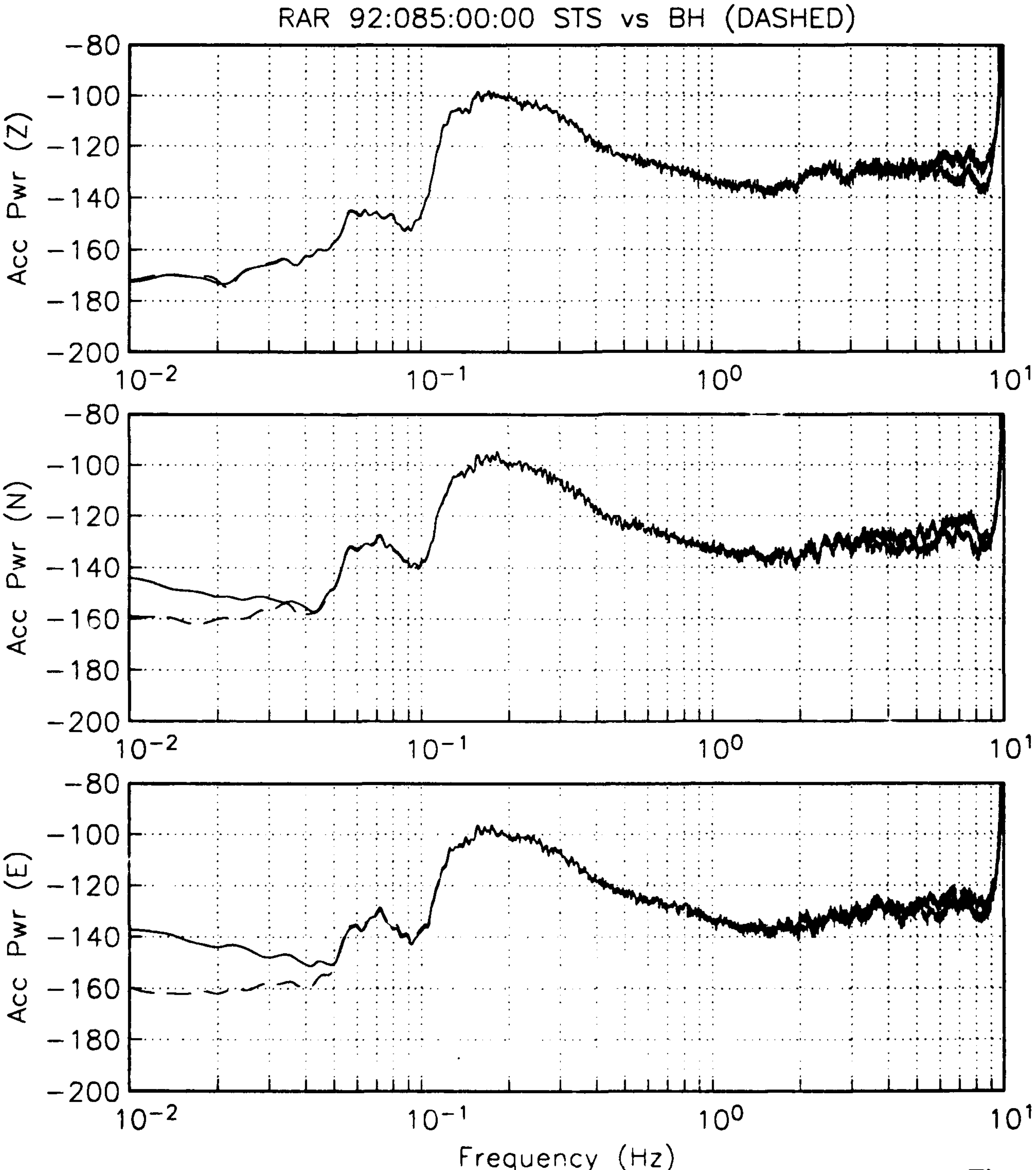
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Acc Pwr (Z)
Acc Pwr (N)
Acc Pwr (E)
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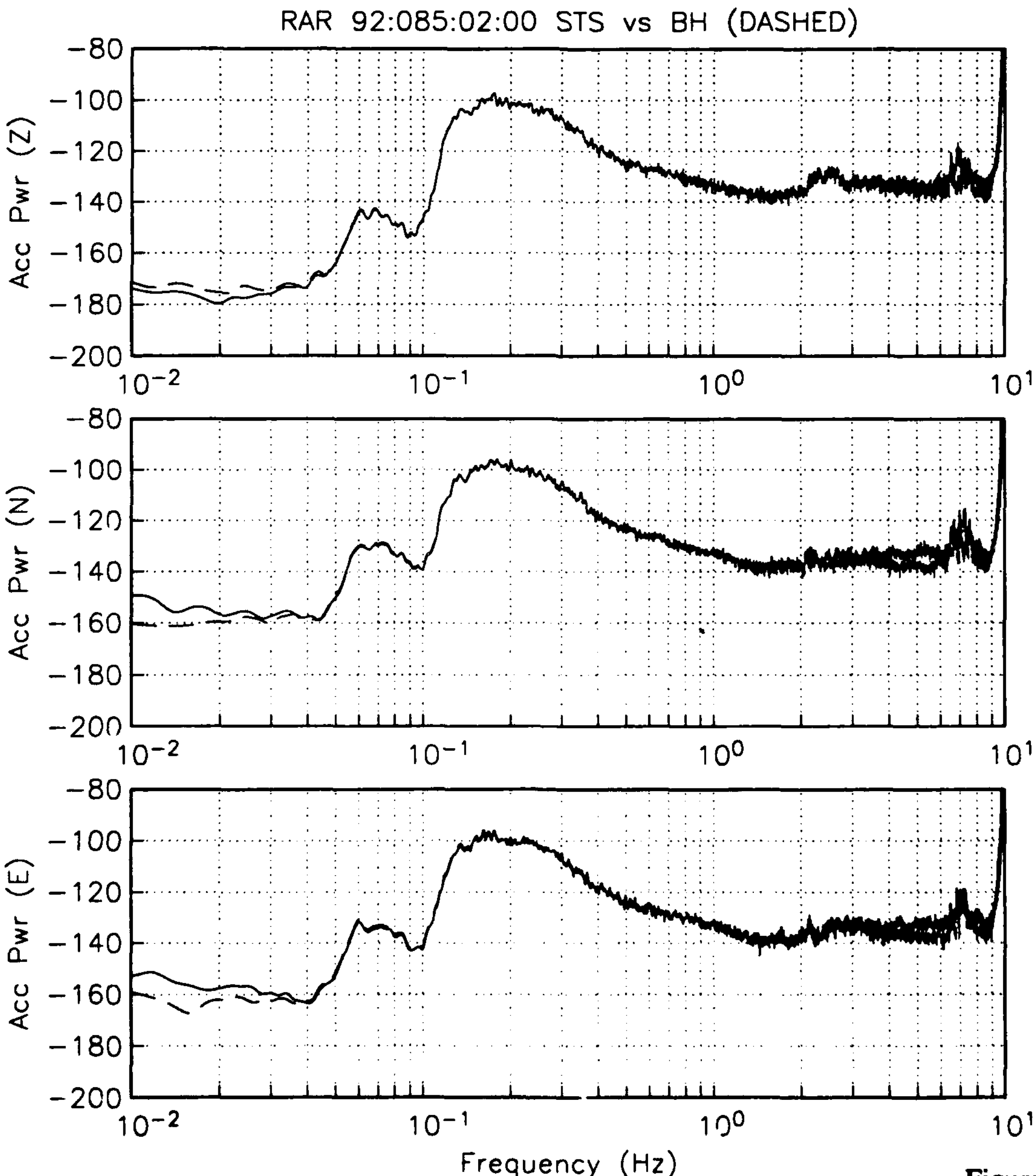
-100
-120
-140
-160
-180
-200
10^{-2}
10^{-1}
10^{0}
10^{1}
Frequency (Hz)

Figure 3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Acc Pwr (N)
Acc Pwr (E)
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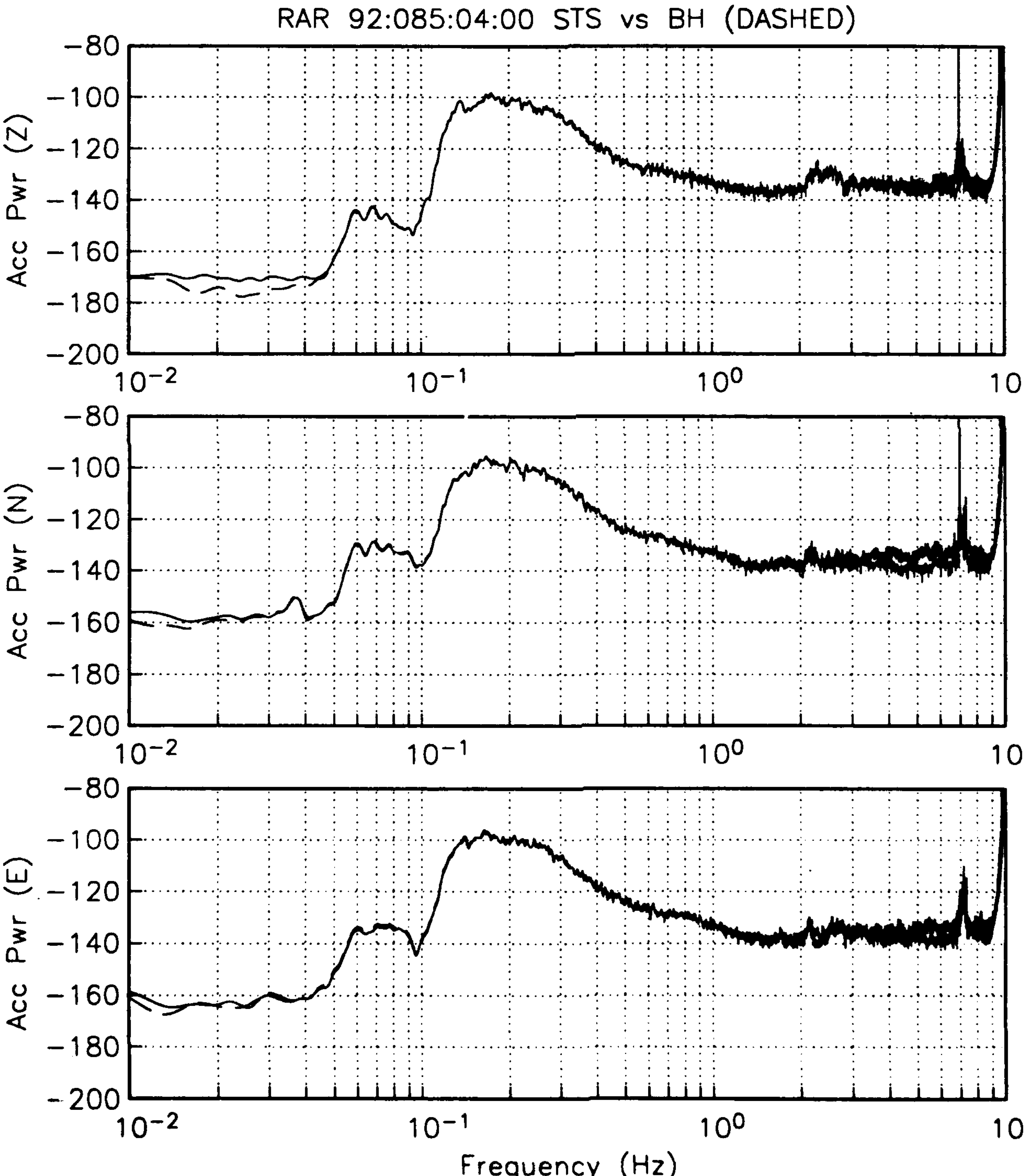
-160
-180
-200
10^{-2}
10^{-1}
10^{0}
10^{1}
Frequency (Hz)

Figure 4



RAR 92:085:04:00 STS vs BH (DASHED)
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Acc Pwr (N)
Acc Pwr (E)
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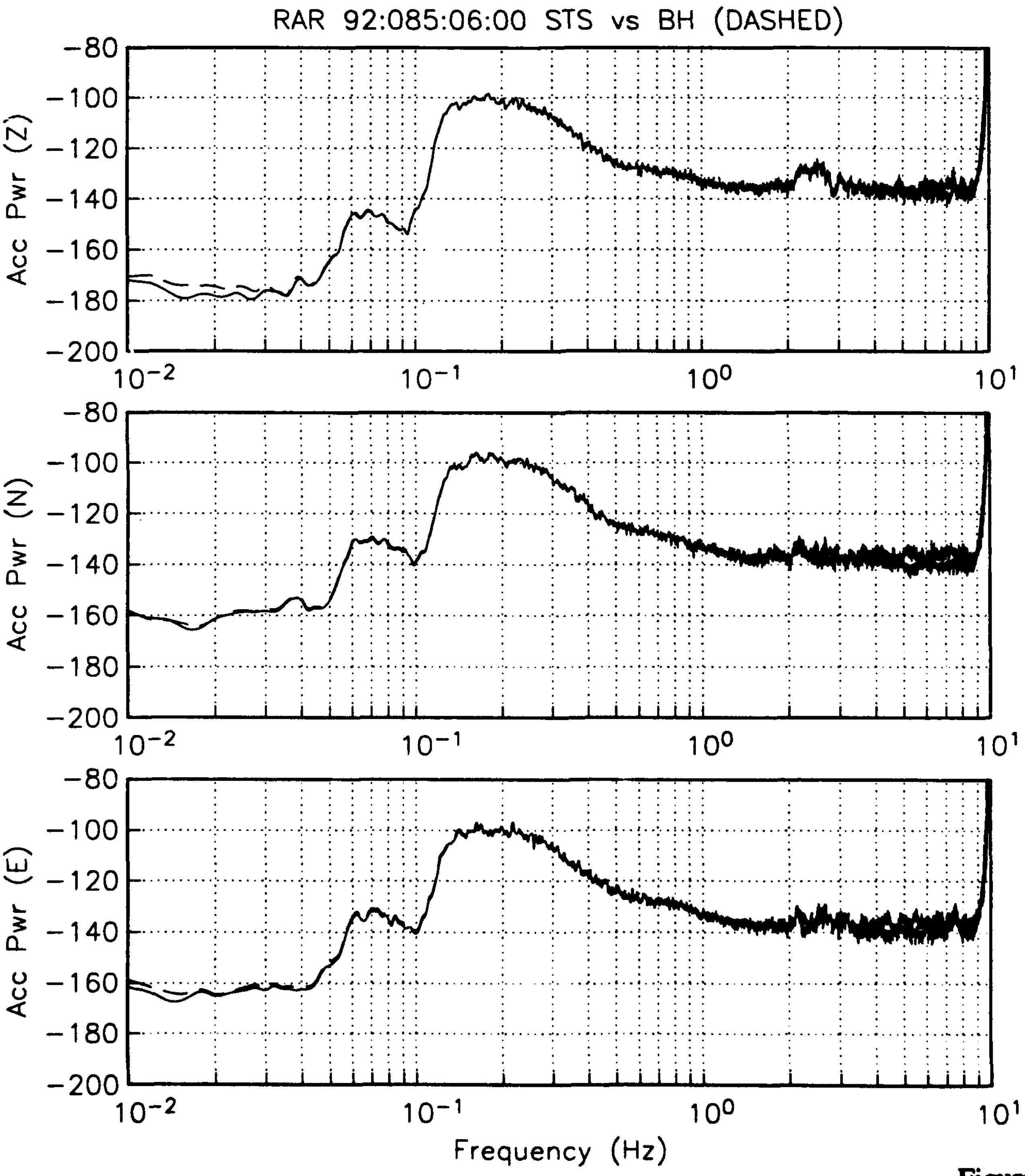
-140
-160
-180
-200
10^{-2}
10^{-1}
10^{0}
10^{1}
Frequency (Hz)

Figure 5



RAR 92:085:06:00 STS vs BH (DASHED)
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Acc Pwr (E)
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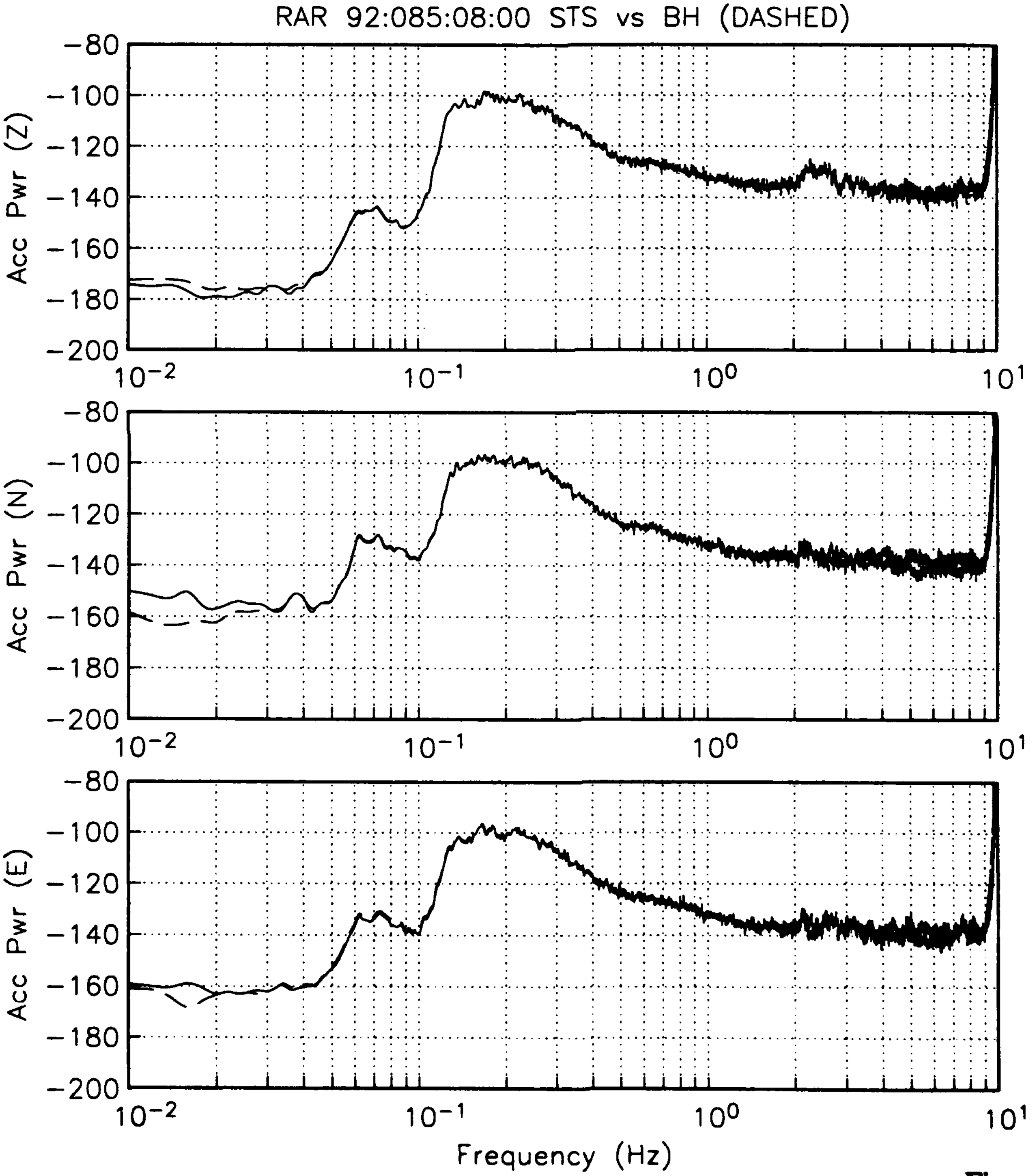
-180
-200
10^{-2}
10^{-1}
10^{0}
10^{1}
Frequency (Hz)

Figure 6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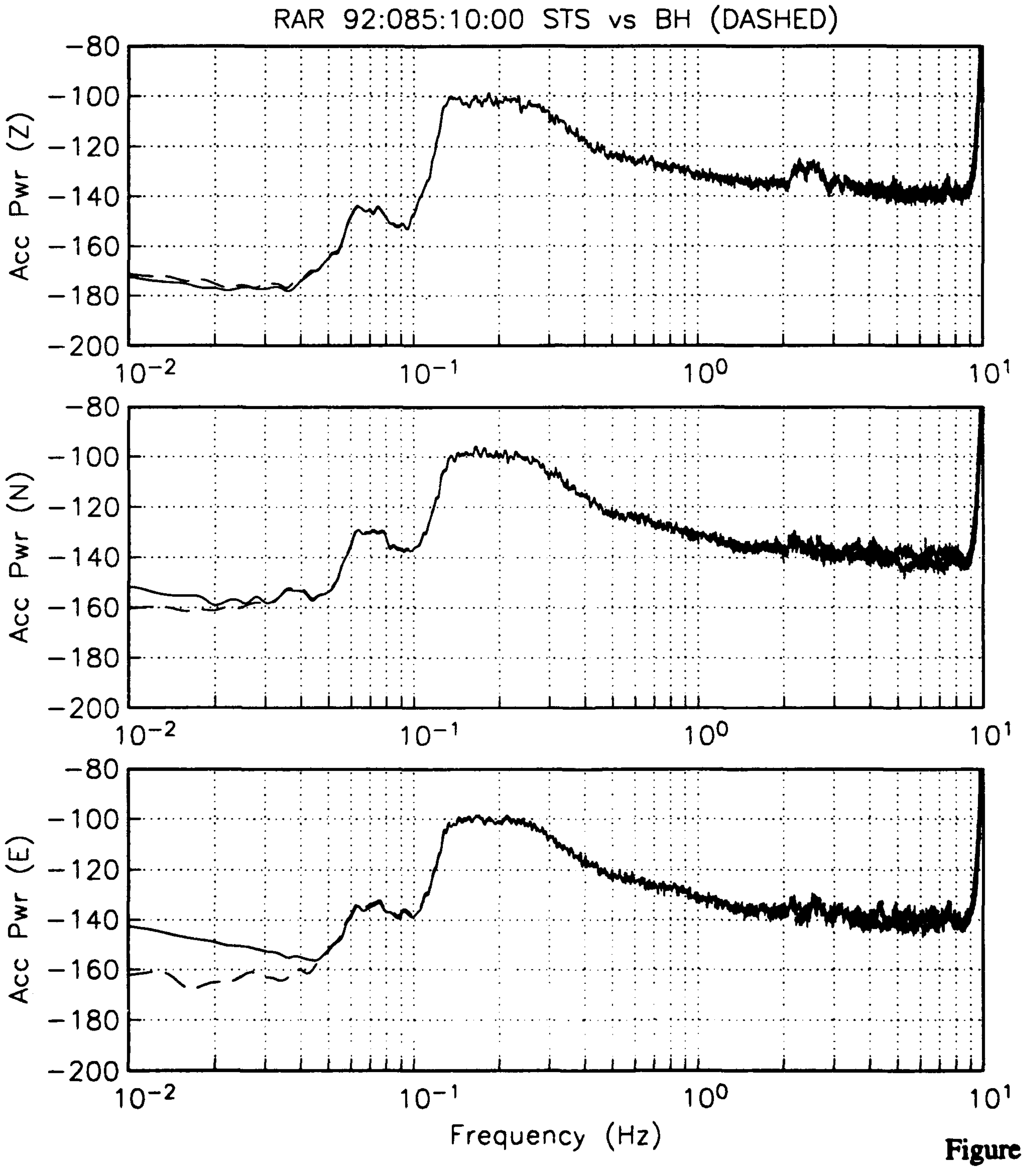
-180
-200
10^{-2}
10^{-1}
10^{0}
10^{1}
Frequency (Hz)

Figure 7



RAR 92:085:10:00 STS vs BH (DASHED)
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Acc Pwr (N)
Acc Pwr (E)
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−160
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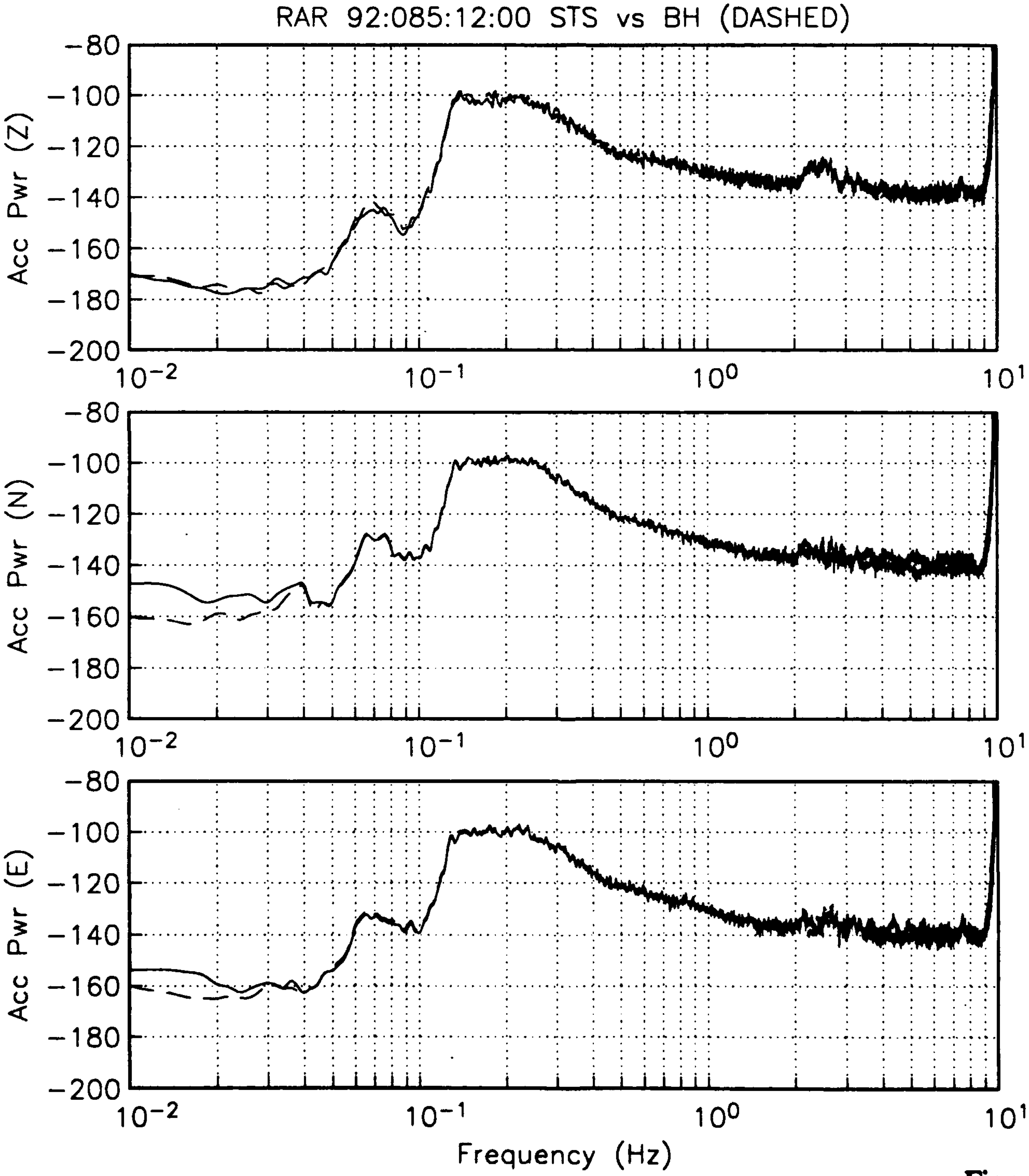
−200
10^{-2}
10^{-1}
10^{0}
10^{1}
Frequency (Hz)

Figure 8



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10^{-1}
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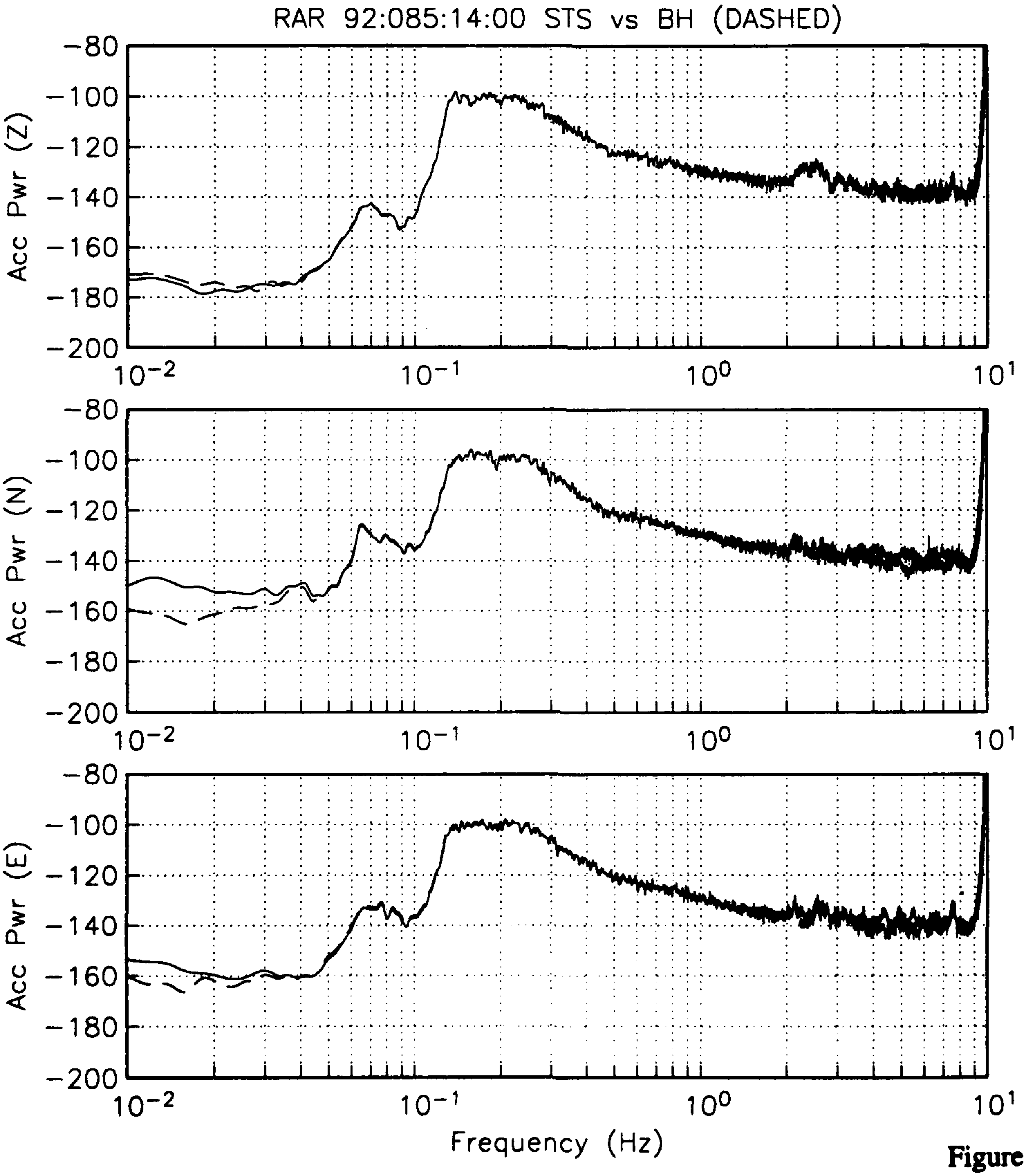
10^{1}
Frequency (Hz)

Figure 9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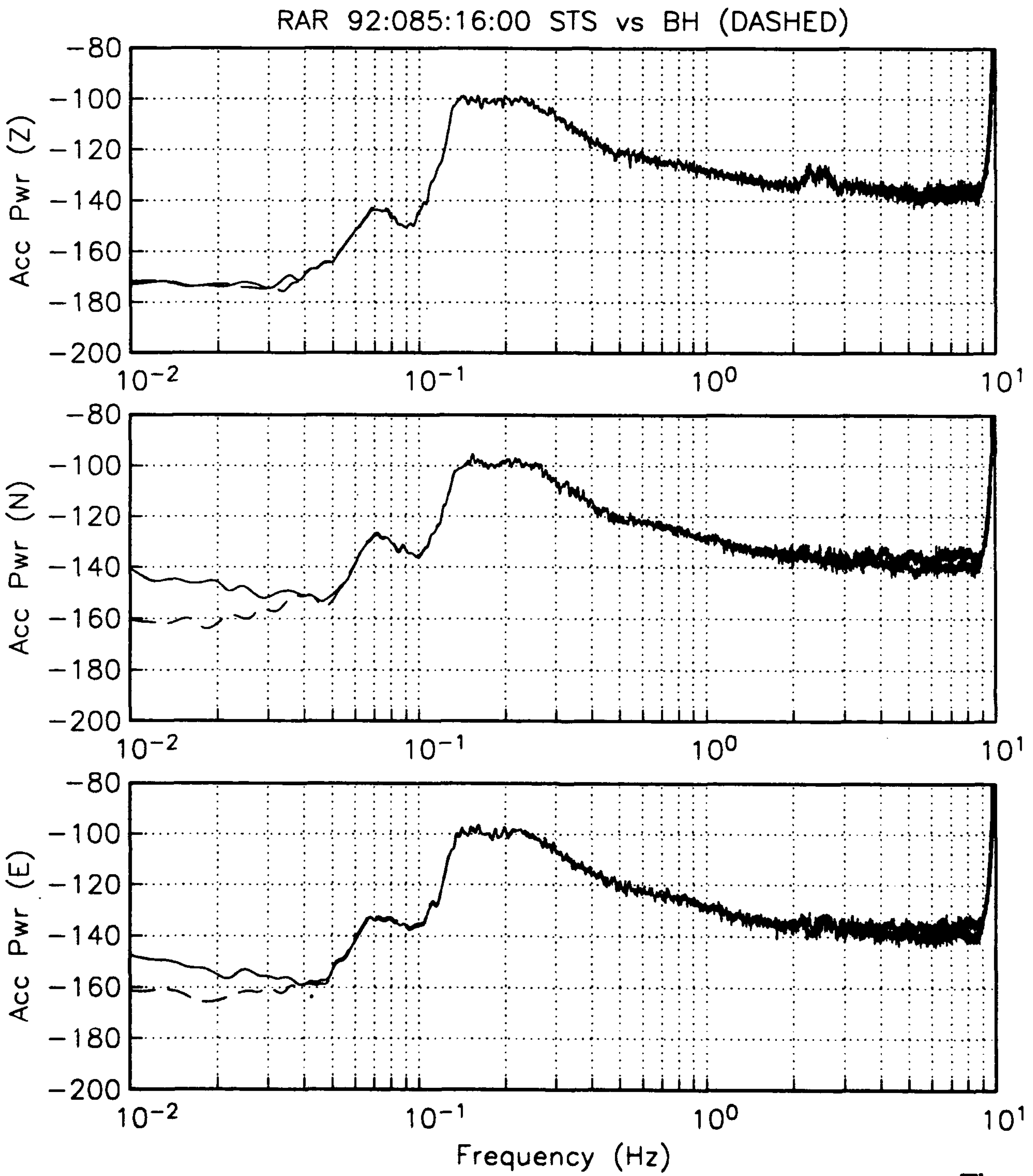
10^{-2}
10^{-1}
10^{0}
10^{1}
Frequency (Hz)

Figure 10


RAR 92:085:16:00 STS vs BH (DASHED)
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Acc Pwr (N)
Acc Pwr (E)
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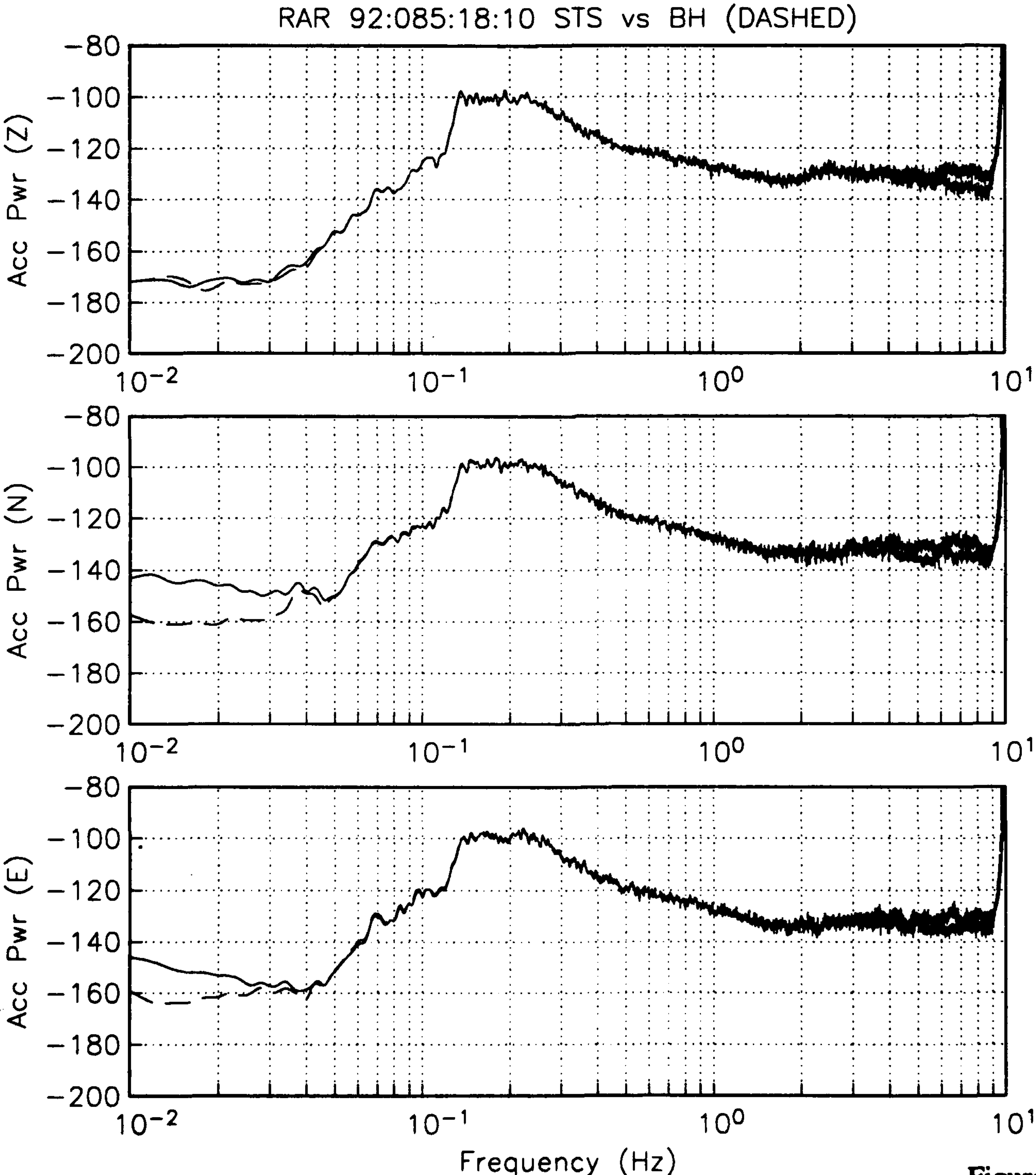
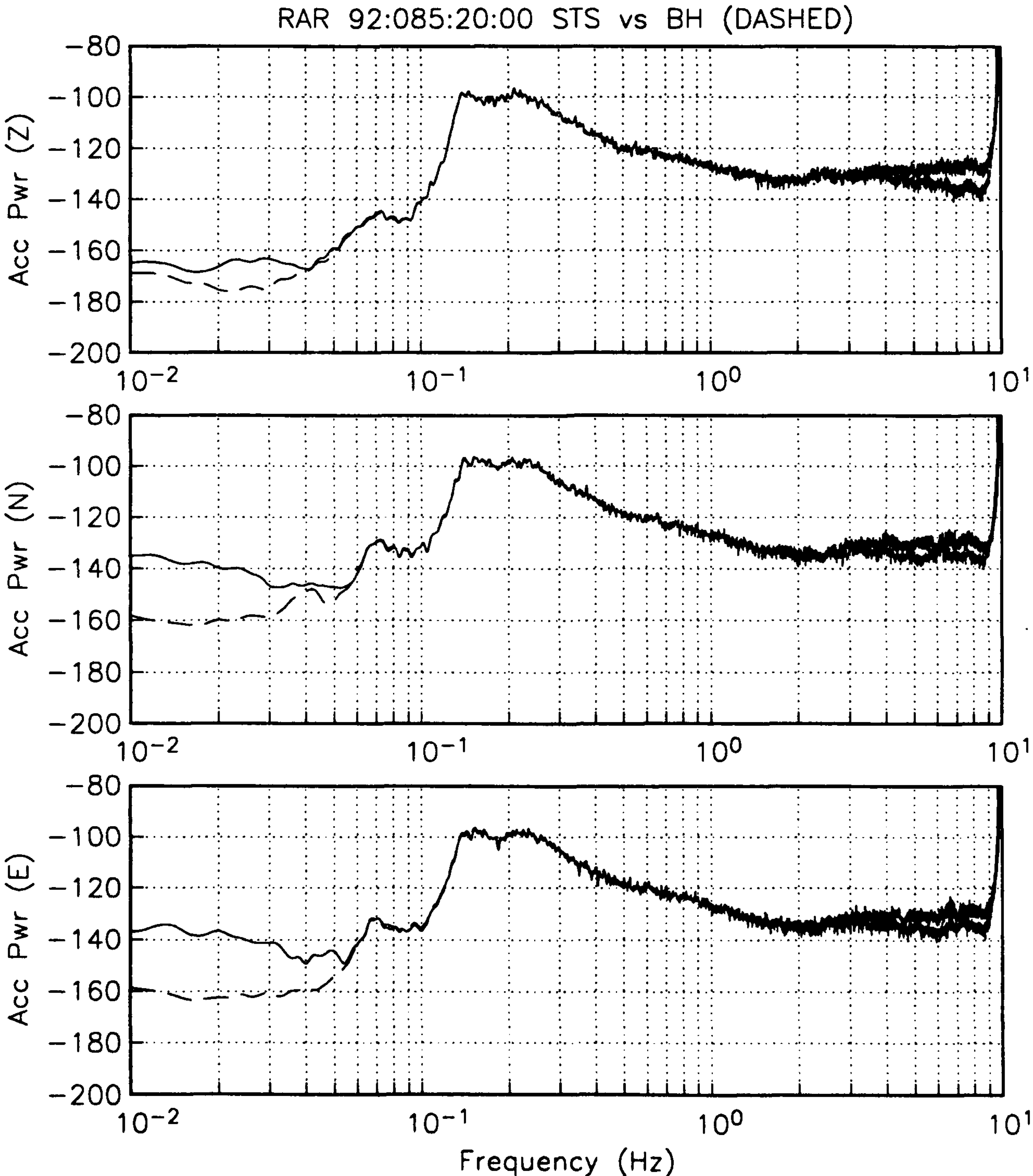
-100
-120
-140
-160
-180
-200
10^{-2}
10^{-1}
10^{0}
10^{1}
Frequency (Hz)

Figure 11



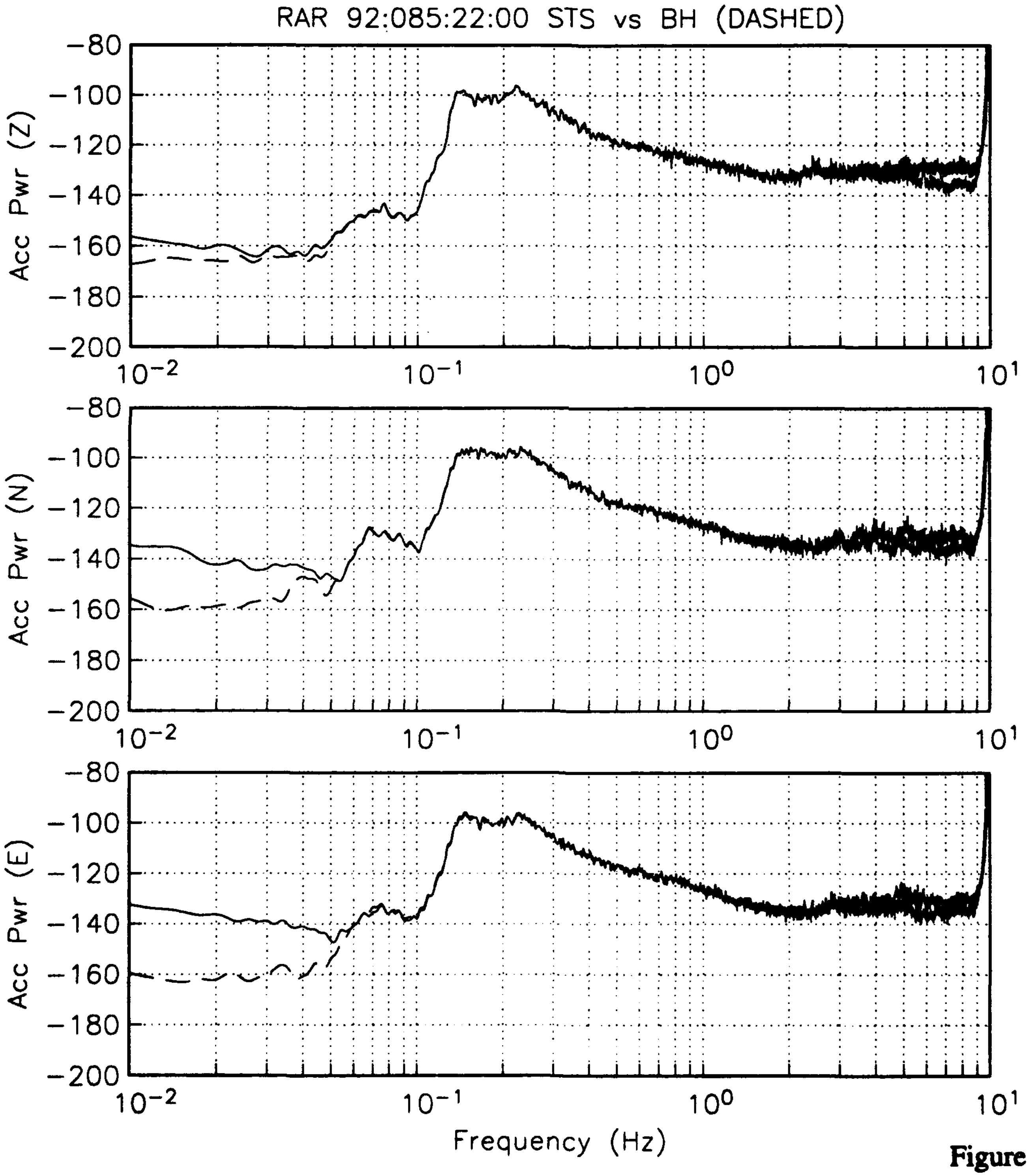
RAR 92:085:18:10 STS vs BH (DASHED)
Acc Pwr (Z)
Acc Pwr (N)
Acc Pwr (E)
-80
-100
-120
-140
-160
-180
-200
10^{-2}
10^{-1}
10^{0}
10^{1}
Frequency (Hz)

Figure 12



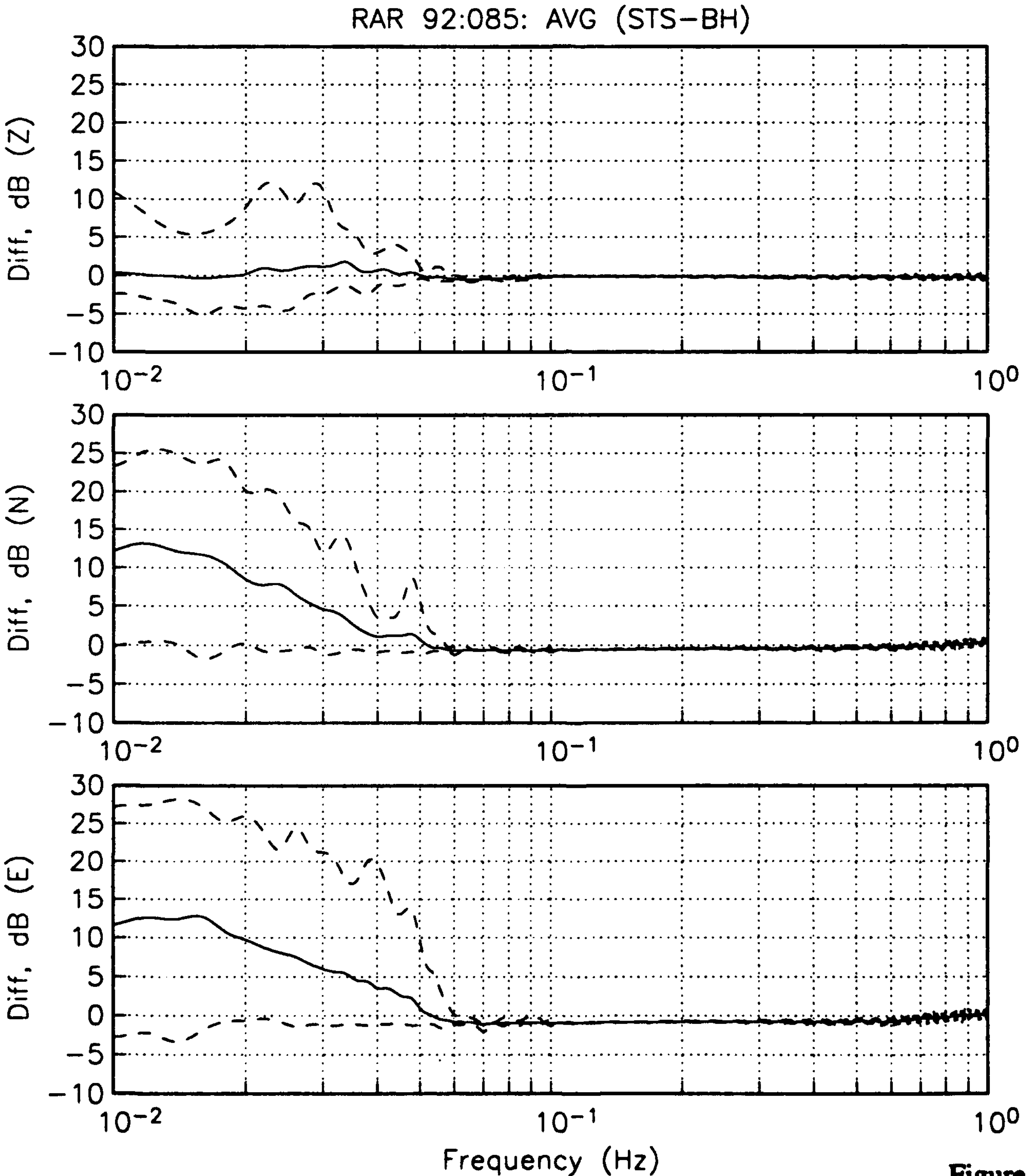
RAR 92:085:20:00 STS vs BH (DASHED)
Acc Pwr (Z)
Acc Pwr (N)
Acc Pwr (E)
-80
-100
-120
-140
-160
-180
-200
10−2
10−1
10^0
10^1
Frequency (Hz)

Figure 13



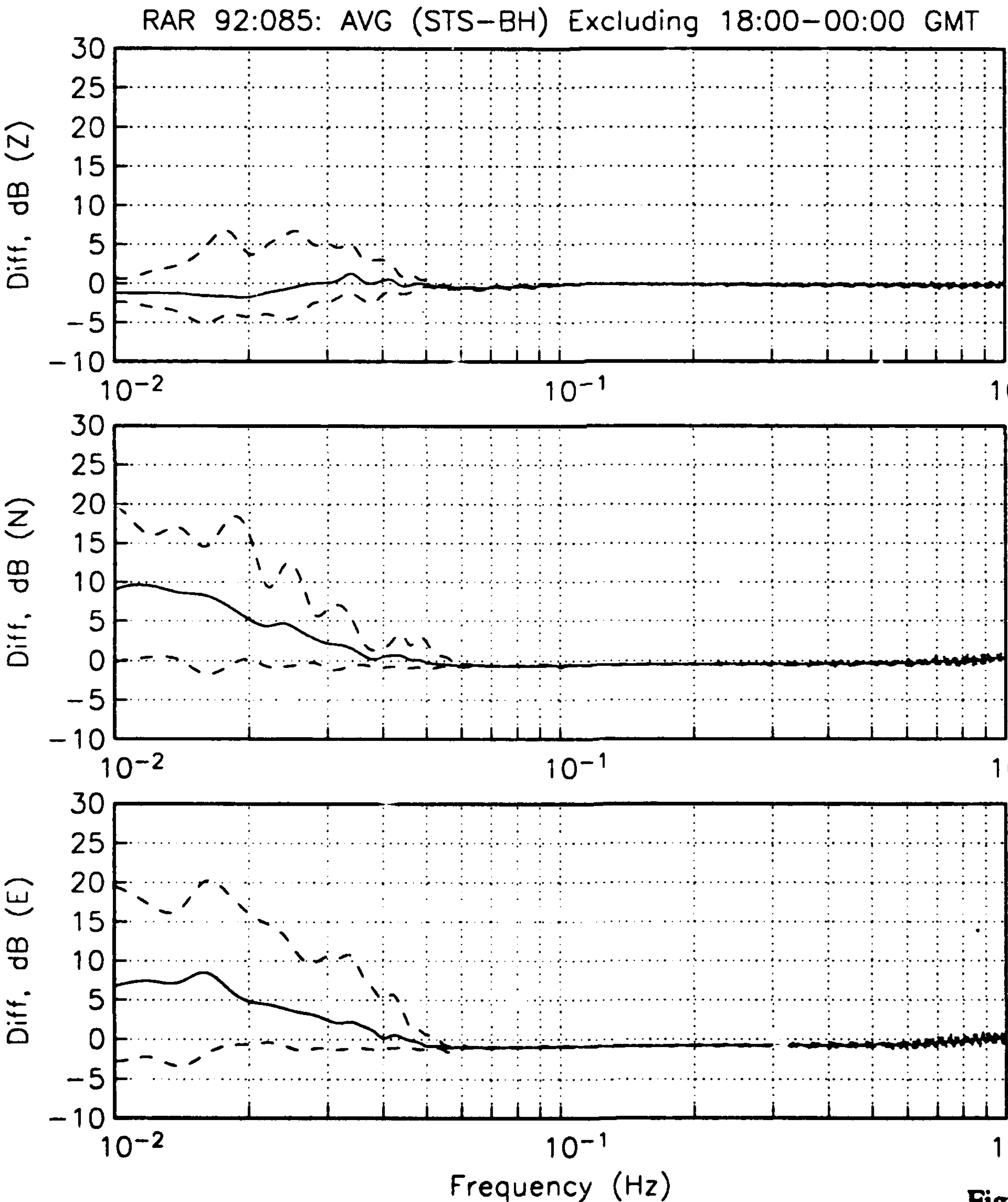
RAR 92:085:22:00 STS vs BH (DASHED)
Acc Pwr (Z)
Acc Pwr (N)
Acc Pwr (E)
-80
-100
-120
-140
-160
-180
-200
10^{-2}
10^{-1}
10^{0}
10^{1}
Frequency (Hz)

Figure 14



RAR 92:085: AVG (STS-BH)
Diff, dB (Z)
Diff, dB (N)
Diff, dB (E)
30
25
20
15
10
5
0
−5
−10
10^{-2}
10^{-1}
10^{0}
Frequency (Hz)

Figure 15



RAR 92:085: AVG (STS−BH) Excluding 18:00−00:00 GMT
Diff, dB (Z)
Diff, dB (N)
Diff, dB (E)
30
25
20
15
10
5
0
−5
−10
10^{-2}
10^{-1}
10^{0}
Frequency (Hz)

Figure 16

Five Days PFO STS-1 Data with Solar Radiation and Wind <1992:130-134>

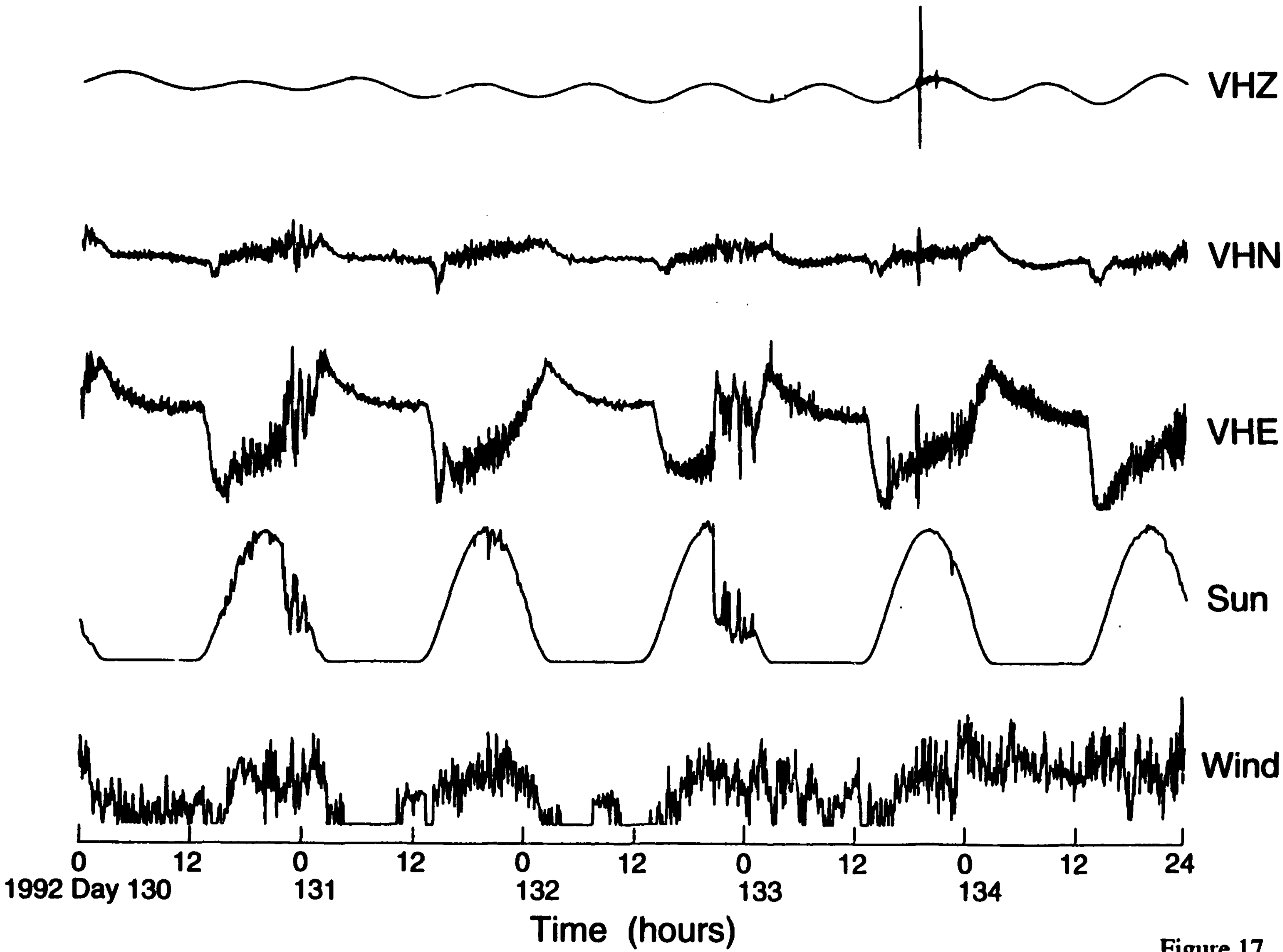


Figure 17

Five Days RPN STS-1 Data <1992:359-363>

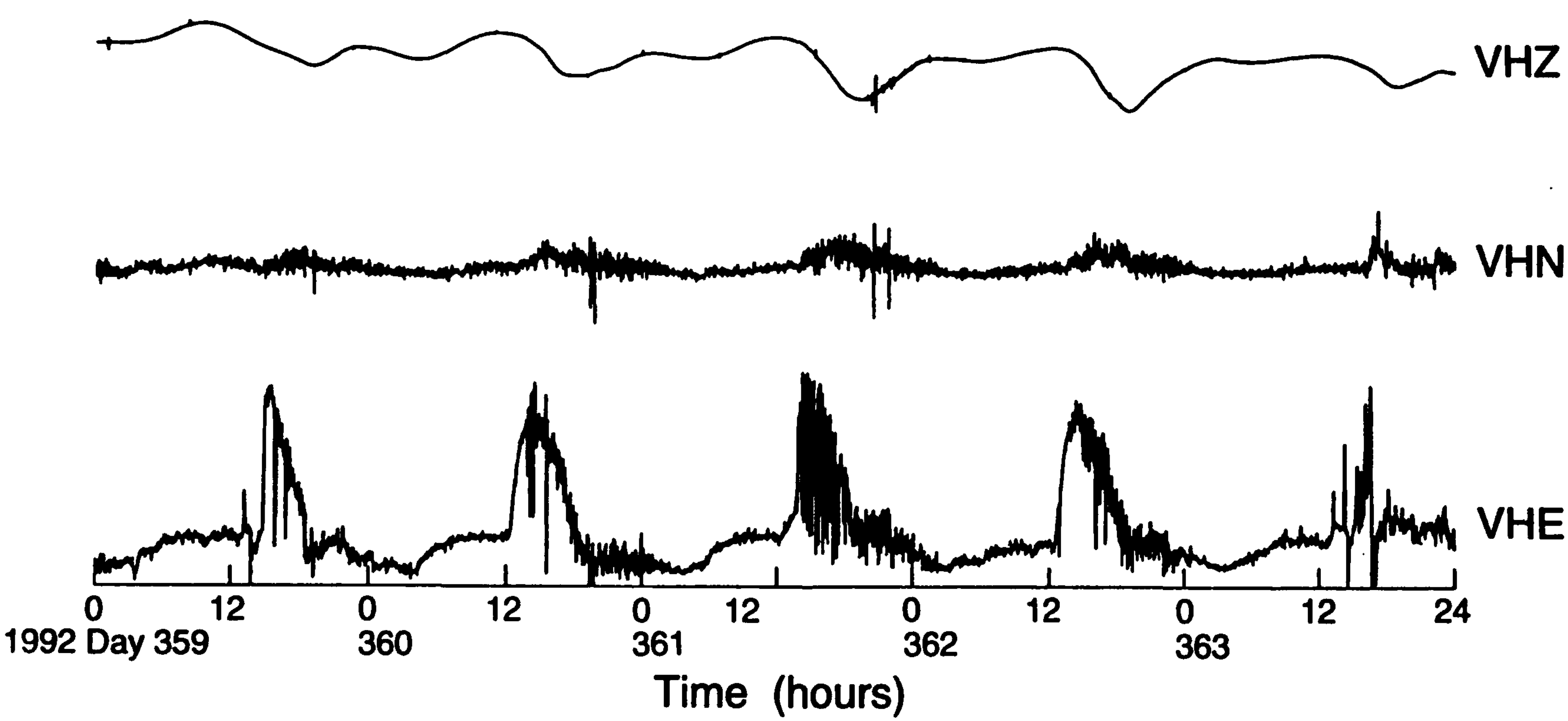


Figure 18

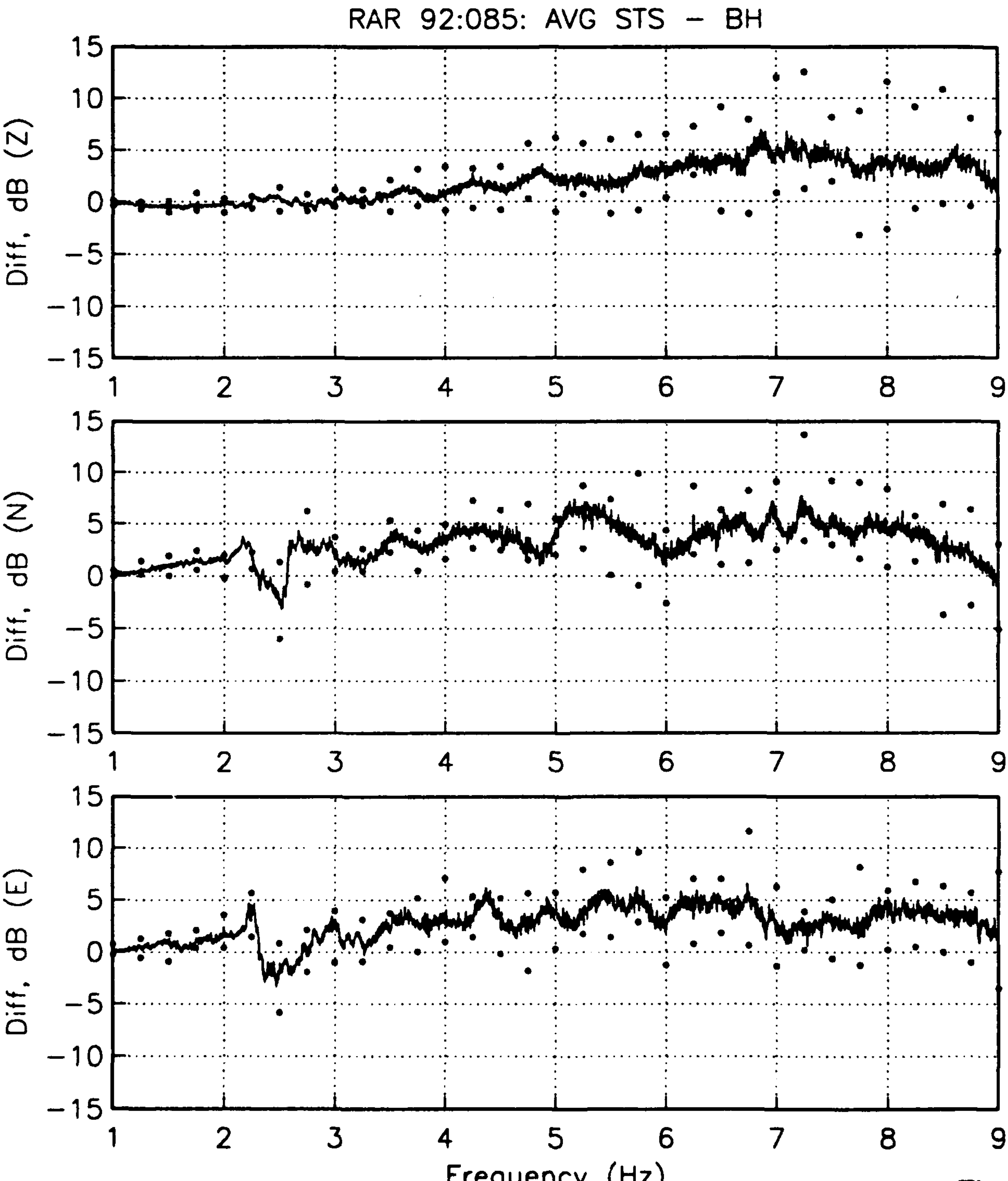

RAR 92:085: AVG STS - BH
Diff, dB (Z)
Diff, dB (N)
Diff, dB (E)
15
10
5
0
−5
−10
−15
1
2
3
4
5
6
7
8
9
Frequency (Hz)

Figure 19

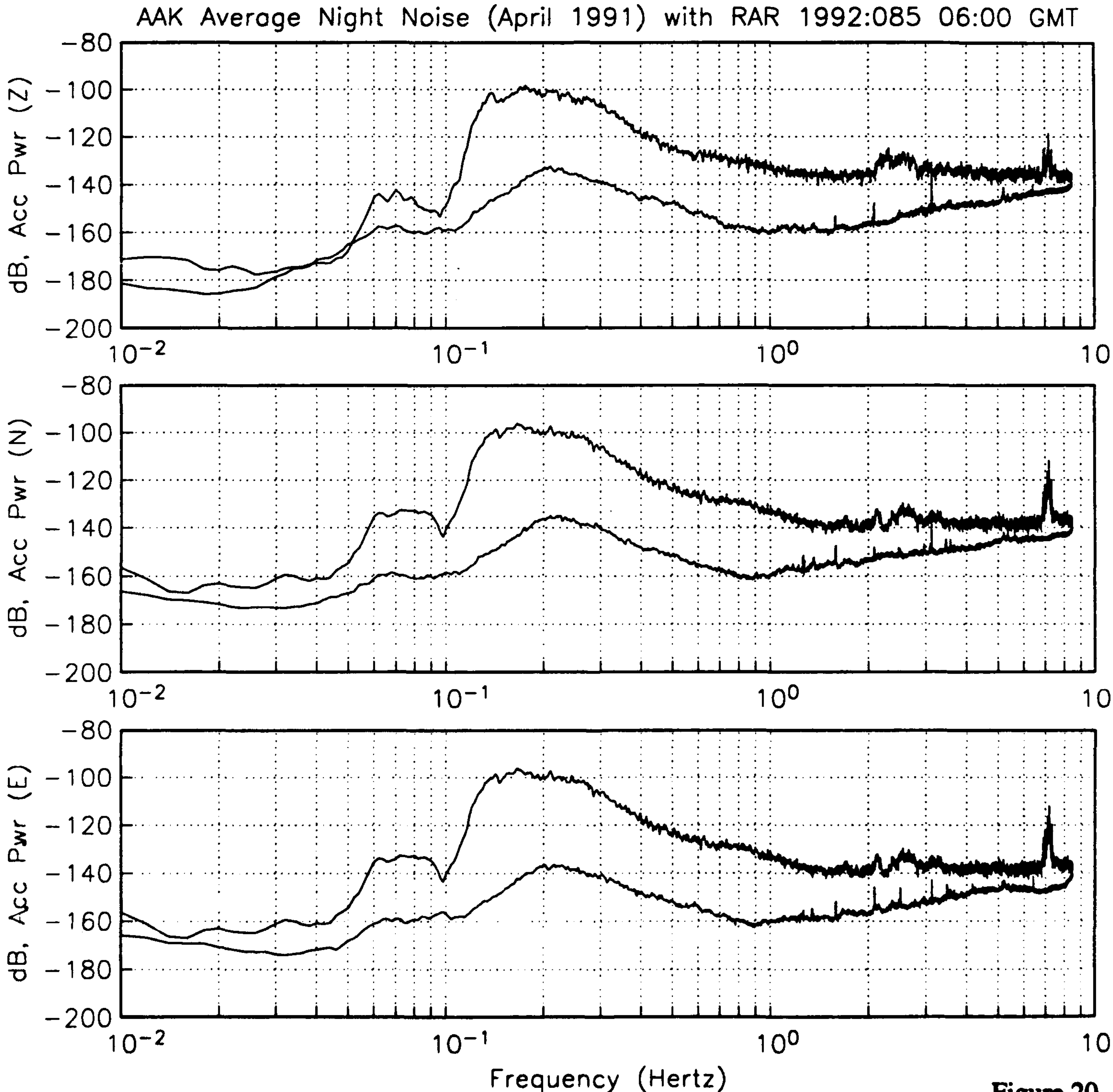

AAK Average Night Noise (April 1991) with RAR 1992:085 06:00 GMT
dB, Acc Pwr (Z)
dB, Acc Pwr (N)
dB, Acc Pwr (E)
-80
-100
-120
-140
-160
-180
-200
10^{-2}
10^{-1}
10^{0}
10^{1}
Frequency (Hertz)

Figure 20