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VELA T/7701

SIGNAL ENHANCEMENT WITH AN ARRAY OF VERTICAL AND HORIZONTAL SEISMOMETERS

ADVANCED ARRAY RESEARCH
Special Report No. 11

Prepared by

Leo N. Heiting   Syed A. Rizvi

John P. Burg, Project Scientist
George D. Hair, Program Manager
Telephone: 1-214-238-3473

TEXAS INSTRUMENTS INCORPORATED
Science Services Division
P.O. Box 5621
Dallas, Texas 75222

Contract:	F33657-67-C-0708-P001
Contract Date:	15 December 1966
Amount of Contract:	$625,500
Contract Expiration Date:	14 December 1967

Sponsored by

ADVANCED RESEARCH PROJECTS AGENCY
Nuclear Test Detection Office
ARPA Order No. 624
ARPA Program Code No. 7F10

28 February 1968

ACKNOWLEDGMENT

This research was supported by the
ADVANCED RESEARCH PROJECTS AGENCY
Nuclear Test Detection Office
under Project VELA UNIFORM
and accomplished under the technical direction of the
AIR FORCE TECHNICAL APPLICATIONS CENTER
under Contract No. F33657-67-C-0708-P001

ABSTRACT

Previous theoretical studies have indicated that arrays consisting of rings of radially oriented horizontal seismometers concentric with a central vertical seismometer are useful for the extraction of P-wave signals from Rayleigh-wave noise. To test this hypothesis, data were recorded at WMO from an experimental array having two horizontal rings and a central vertical seismometer. This report presents the results of processing the data.

The two multichannel processors designed were a conventional Wiener infinite-velocity signal-extraction filter and an adaptive prediction-error filter. The Wiener processor, which was the better of the two, yielded about 4-db noise suppression over the 0.0- to 3.0-Hz frequency range. Both processors showed some signal distortion.

Below 1.0 Hz, this poor performance is not surprising since, in this range, WMO is known to have a high level of P-wave noise which cannot be suppressed effectively by this type of array. At higher frequencies, however, much greater SNR improvement is to be expected. Examination of the recordings shows a great deal of variability along the individual horizontal-seismometer outputs and from output to output. This, coupled with the poor performance of the processors, suggests that the records contain a high level of nonseismic noise.

ACRONYMS

MCP	Multichannel prediction filter
NS3	Noise sample 3
NSB	Noise sample B
SNR	Signal-to-noise ratio
SSA	Signal sample A
SSB	Signal sample B
TFO	Tonto Forest Seismological Observatory
WMO	Wichita Mountains Seismological Observatory

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SECTION I
INTRODUCTION

Previous theoretical studies indicated that arrays consisting of rings of radially oriented horizontal seismometers concentric with a central vertical seismometer are useful for extracting P-wave signals from Rayleigh-wave noise.[1,2] Multichannel prediction filters use the horizontal seismometer traces to predict the Rayleigh-wave component of the vertical seismometer trace. The near-vertically-arriving P-wave signal, which has only a small horizontal component, remains relatively undisturbed in the prediction-error trace.

In the second half of 1967, an experimental array of this type was installed at the Wichita Mountains Seismological Observatory (WMO). It included a vertical seismometer and two rings of six horizontal seismometers each, with diameters of 1.15 and 2.0 km, respectively. Data from this array were recorded digitally during September and October 1967. To date, there has been a limited amount of processing on these data —including the design of conventional and adaptive multichannel filters and evaluation of two recorded events — in an effort to verify experimentally the theoretical results. The results, which must be regarded as inconclusive, are presented and discussed in this report. Also included are suggestions for a more detailed data analysis directed toward a better understanding of the performance of this array.

Two events with moderately strong PKP phases, as well as a 20-min noise sample preceding the second event, were selected for the study. Wiener infinite-velocity signal-extraction and adaptive prediction-error filters were designed from, and applied to, the data. Spectra comparisons for the filtered and unfiltered signal samples and the noise sample show only about 2-db signal-to-noise improvement using either processor.

This poor performance is not totally unexpected below 1.0 Hz, where the WMO noise field is known to be largely P-wave noise.[3] Between 1.0 and 3.0 Hz, however, such meager improvement is surprising.

Examination of the horizontal-seismometer noise recordings shows a disturbing amount of dissimilarity between traces and variability along a number of the individual traces; this fact, coupled with the poor results obtained, suggests that the data may be seriously contaminated by random nonseismic noise. Consequently, the multichannel filter results obtained with the data are questionable.

One 30-min noise sample recorded in September appears visually to be much better behaved than the data just discussed. This sample has not been analyzed to date, since no usable events were obtained at the time of its recording. Now, this noise sample, it appears, will be useful for determining more conclusively why better performance has not been realized with this array.

The absolute level of a previously published spectrum was subject to some question because of uncertainties in the calibration information.[3] Therefore, an absolute power-density spectrum of the vertical noise was computed from data recorded by one of the permanent shallow-buried instruments (U3).

SECTION II

DESCRIPTION OF ARRAY AND DATA

At WMO, horizontal Benioff seismometers H_1 through H_{12} were oriented radially around two rings concentric with a central vertical seismometer Z_{10} (Figure 1). Seismometers H_1 through H_{12} were located on the surface, and Z_{10} was buried to a depth of 10 ft. In addition to the one vertical and the 12 horizontal seismometers, which are regarded as near-surface seismometers, another set of 13 vertical seismometers U_1 through U_{13} were buried to a depth of 200 ft; these are regarded as shallow-hole seismometers and are marked accordingly in Figure 1. The shallow-hole seismometers were not used in the design of the multichannel filters, but the data obtained from them were used to compute the absolute power spectrum of the noise.

Of the several noise and signal samples collected during September and October 1967, one 159.4-sec signal sample from the 19 September 1967 data was selected for processing. Later, another 159.4-sec sample was selected from the 5 October 1967 data; also, from data of the same day, a 20-min noise sample preceding the 159.4-sec signal was selected for processing. This latter noise sample is not continuous; a 6-min break separates the noise and signal samples. Table 1 shows the labeling scheme and gives the events' times of observation and epicenters.

Noise sample NSB and the two signal samples SSB and SSA were antialias-filtered and decimated to a foldover frequency of 3.0 Hz. Then, the decimated data were whitened prior to the design of the multichannel filters (Wiener and adaptive).

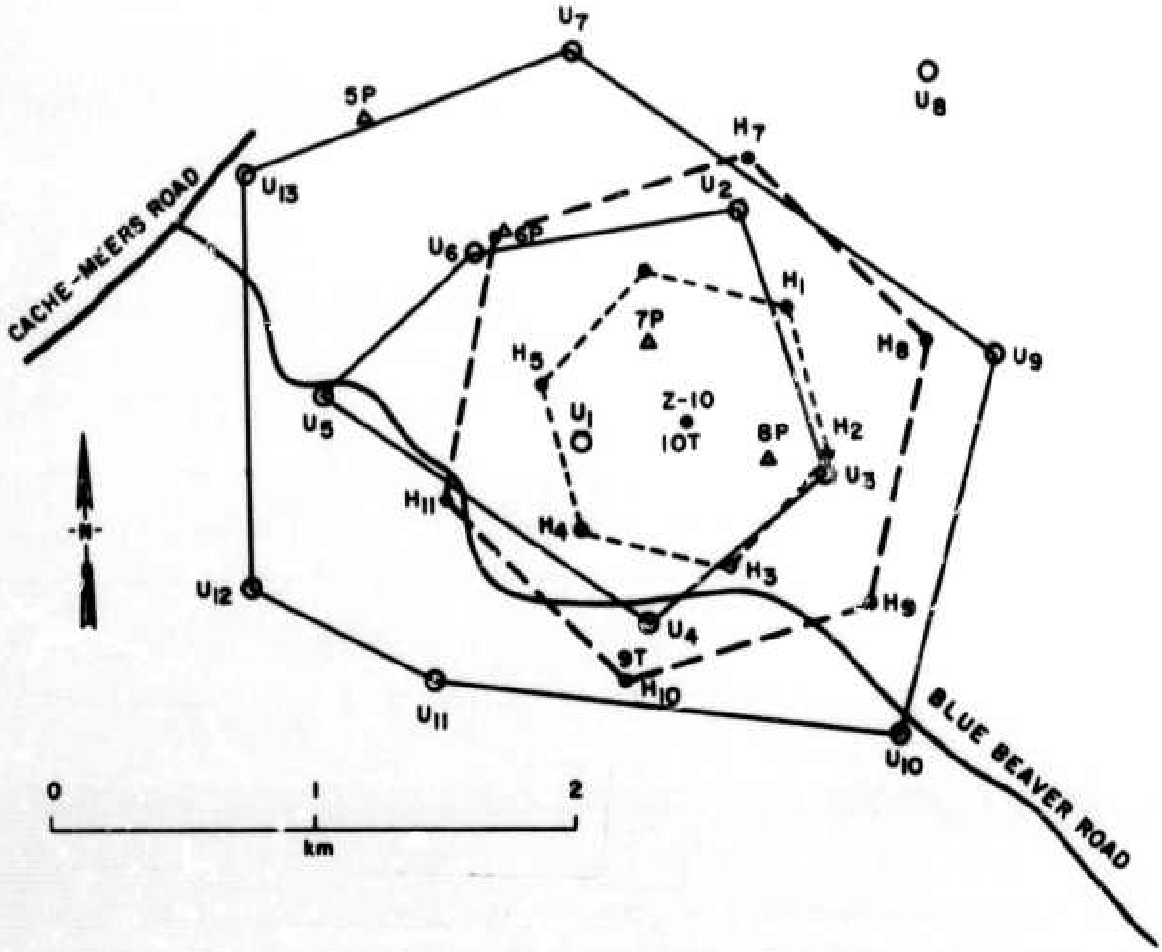

Figure 1. Array Layout at WMO

Table 1

EVENT INFORMATION

Label	Date (1967)	Arrival Time (GCT)	Epicenter Δ	Epicenter Azimuth	Phase	Magnitude (m_b)
SSA signal sample A	19 Sep	19:21:08.4	142.5°	-26.3°	PKP	5.0
SSB signal sample B	5 Oct	17:59:28.9	144.8°	-38.3°	PKP	4.6
NSB noise sample B	5 Oct	Preceding SSB	Not Applicable			

SECTION III

FILTER DESIGN AND EXPERIMENTAL RESULTS

A. FILTER DESIGN

Wiener signal-extraction and adaptive prediction-error filters were designed from previously whitened noise sample B (NSB) and applied to signal sample A (SSA), signal sample B (SSB), and NSB. All filters were 25 points in length.

The Wiener signal-extraction filter was designed from the 20-min prewhitened NSB, using a theoretical infinite-velocity signal model with the same spectrum as that of the vertical seismometer noise and with a signal-to-noise ratio of 4. The filter was then applied to NSB, SSB, and SSA (all having been previously whitened).

An adaptive prediction-error filter was also run on SSA, SSB, and NSB. Because the program could not handle more than 5000 points, the 20-min NSB was shortened to 14 min and was then equivalent to 5000 points. The 12 horizontal seismometers were used to predict the noise on vertical seismometer Z_{10}. Starting with all filter coefficients set equal to 0 and k_s (the convergence parameter in the adaptive algorithm) set equal to 0.0001, the first 1000 points of NSB were processed. Filter coefficients thus obtained from the first pass were then used in the second pass on the same 1000 points, setting $k_s = 0.00005$. This process was repeated twice more, with $k_s = 0.000025$ and 0.000012.

The mean-square-error for each value of k_s was also computed. Figure 2 shows the decrease in the mean-square-error with the decrease in k_s.

These passes through the data constitute a training cycle for the filters. In a practical on-line adaptive-filter application, the filters would continuously update themselves, making this training cycle unnecessary.

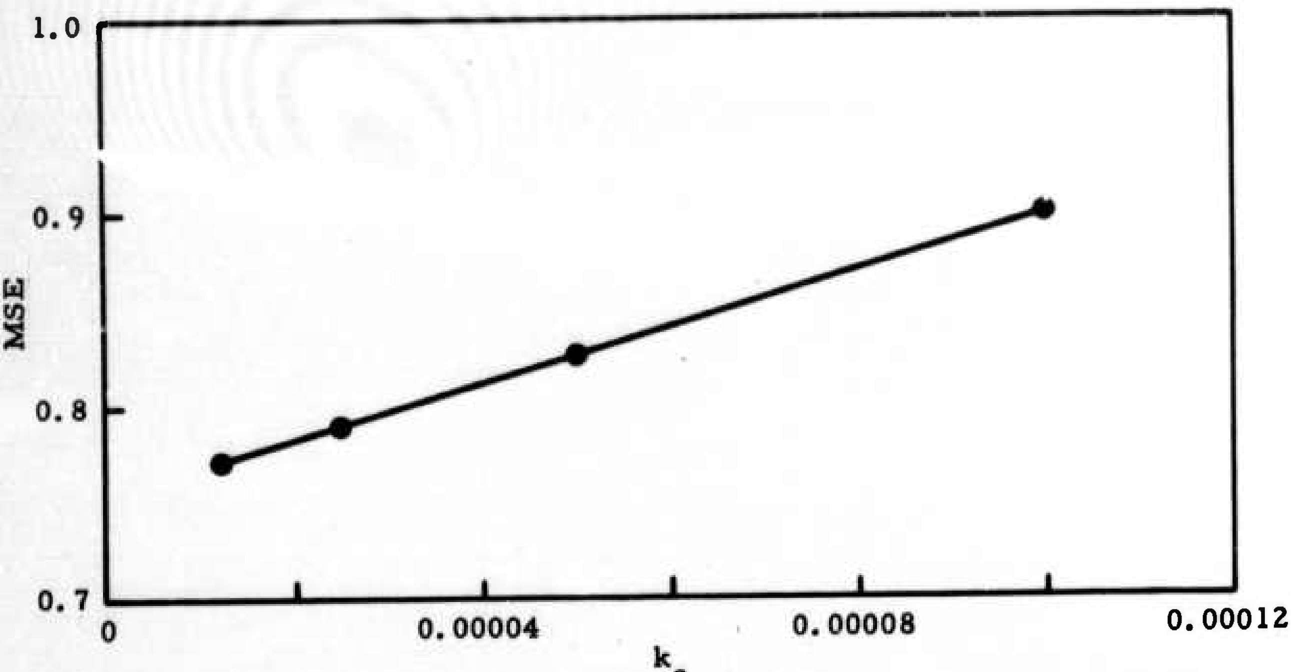

Figure 2. Mean-Square-Error Vs k_s for NSB, 1000 Points

The mean-square-error started from 0.9 in the first pass and reduced to 0.77 in the fourth pass. The filter thus obtained from the fourth pass was used with $k_s = 0.000006$; this time, however, all of the 5000 points were used, and the mean-square-error was found to be 0.78. In all the passes mentioned, including the pass on 5000 points, the filter was constantly adapting to the noise. The filter thus obtained was then applied to SSA and SSB, each of which was 159.4-sec in length.

To meet a program requirement that the number of points to be processed be an integral multiple of 250, the 949 points (159.4 sec) were cut to 750 points (126.1 sec); this was done to both SSA and SSB. To prevent the filter coefficients from becoming excessively large while adapting, they were frozen at iterations when the square of the error (at those points) was greater than some factor times the average value of the squares of the data in the horizontal traces. In other words, the filter coefficients were frozen where $\epsilon_t^2 >$ (α x average value of the squares of the data in the horizontal traces). Three passes were made, with $\alpha = 1.0$ for the first pass and $\alpha = 1.5$ and 2.0 for the second and third passes. Table 2 gives the number of points on which the filter coefficients froze in each pass.

Table 2

NUMBER OF POINTS ON WHICH THE COEFFICIENTS FROZE

Pass	α	No. of Points	
		SSA	SSB
First	1.0	300	66
Second	1.5	256	33
Third	2.0	211	23

The original unfiltered vertical seismometer traces of SSA and SSB, as well as their Wiener outputs, are presented in Figure 3. Figure 4 shows the original SSA and SSB traces, their predicted values obtained from the adaptive filters, and the error traces.

B. EXPERIMENTAL RESULTS

The power spectra of the original trace, the Wiener output, and the error trace obtained from the adaptive output have been computed for NSB, SSA, and SSB and are presented in Figures 5, 6, and 7.

The poor performance of the filters below 1.0 Hz was consistent with the results of a previous study, where the P-wave energy was found to be the major noise constituent in this range.[3]

The filters, as can be seen from Figures 3 through 7, were unable to suppress the noise level appreciably; hence, the signal enhancement appears to be very poor. The maximum attenuation of the noise (Figure 5), using the Wiener filter, was about 4.5 db; the adaptive filter attenuated the noise by 2.0 db.

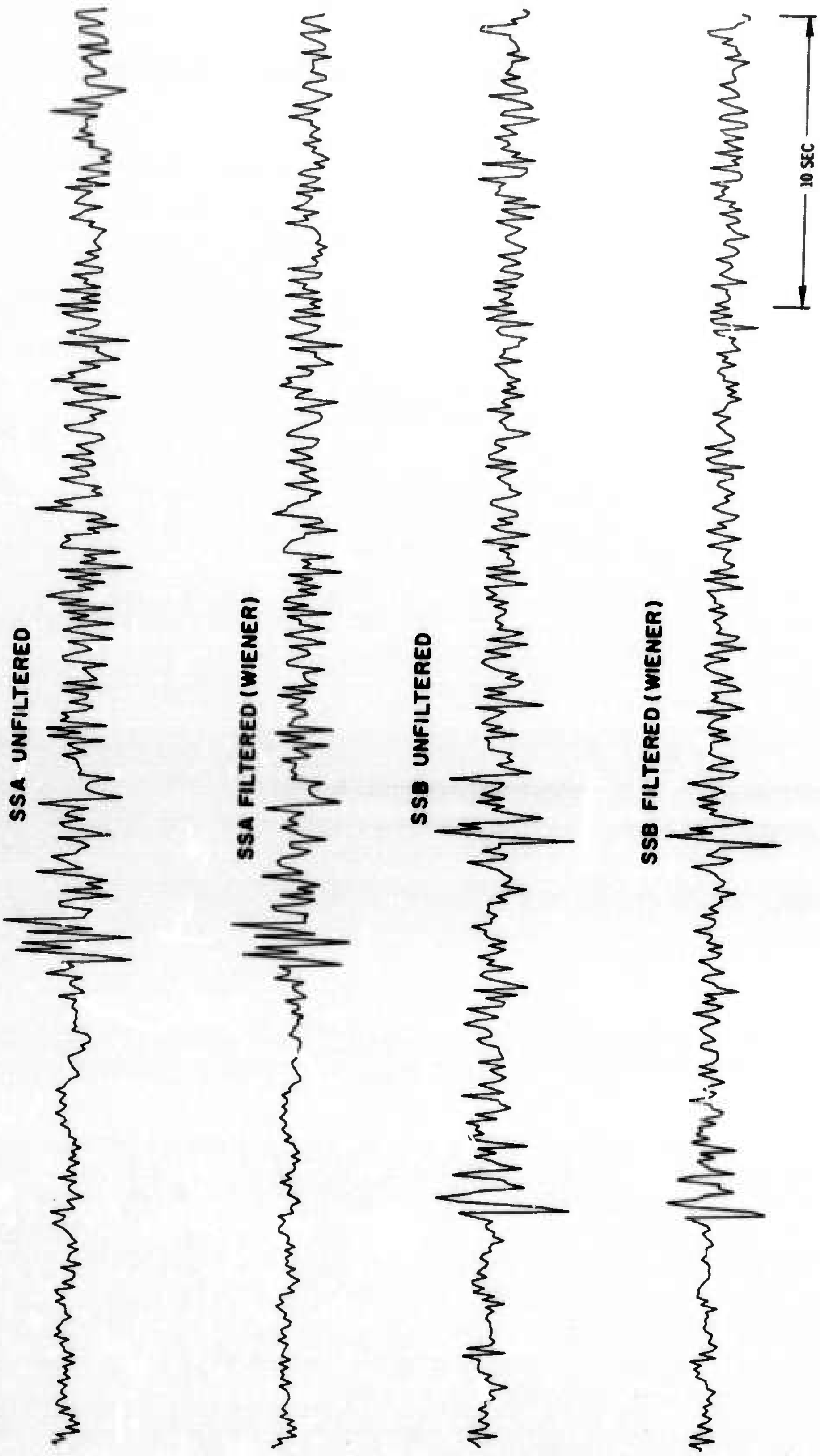

Figure 3. Unfiltered and Filtered (Wiener Output) Traces for SSA and SSB

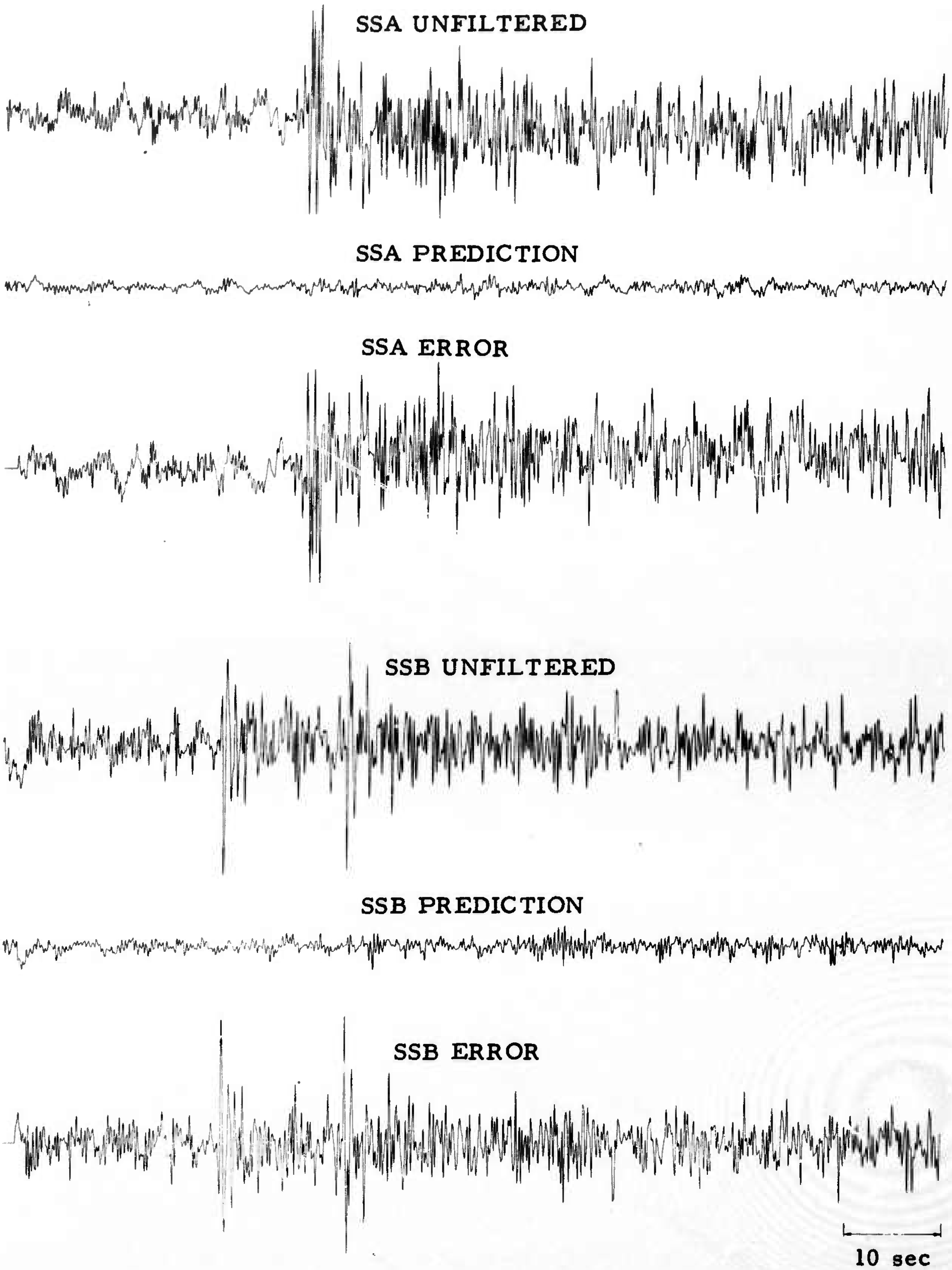

Figure 4. Unfiltered, Prediction, and Prediction-Error (Adaptive Output) Traces for SSA and SSB

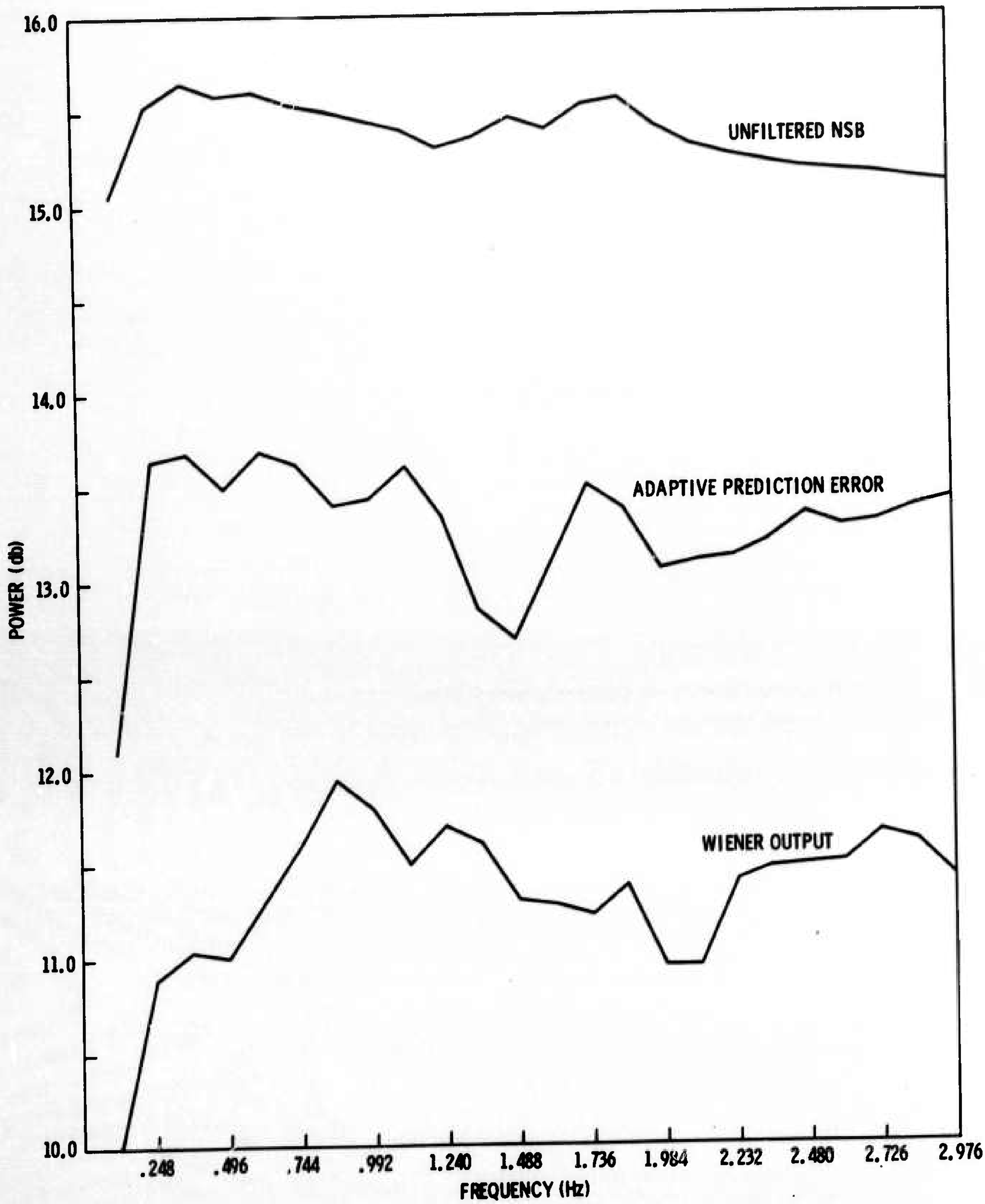

Figure 5. Power Spectra NSB: Unfiltered, Wiener Output, and Adaptive Prediction Error

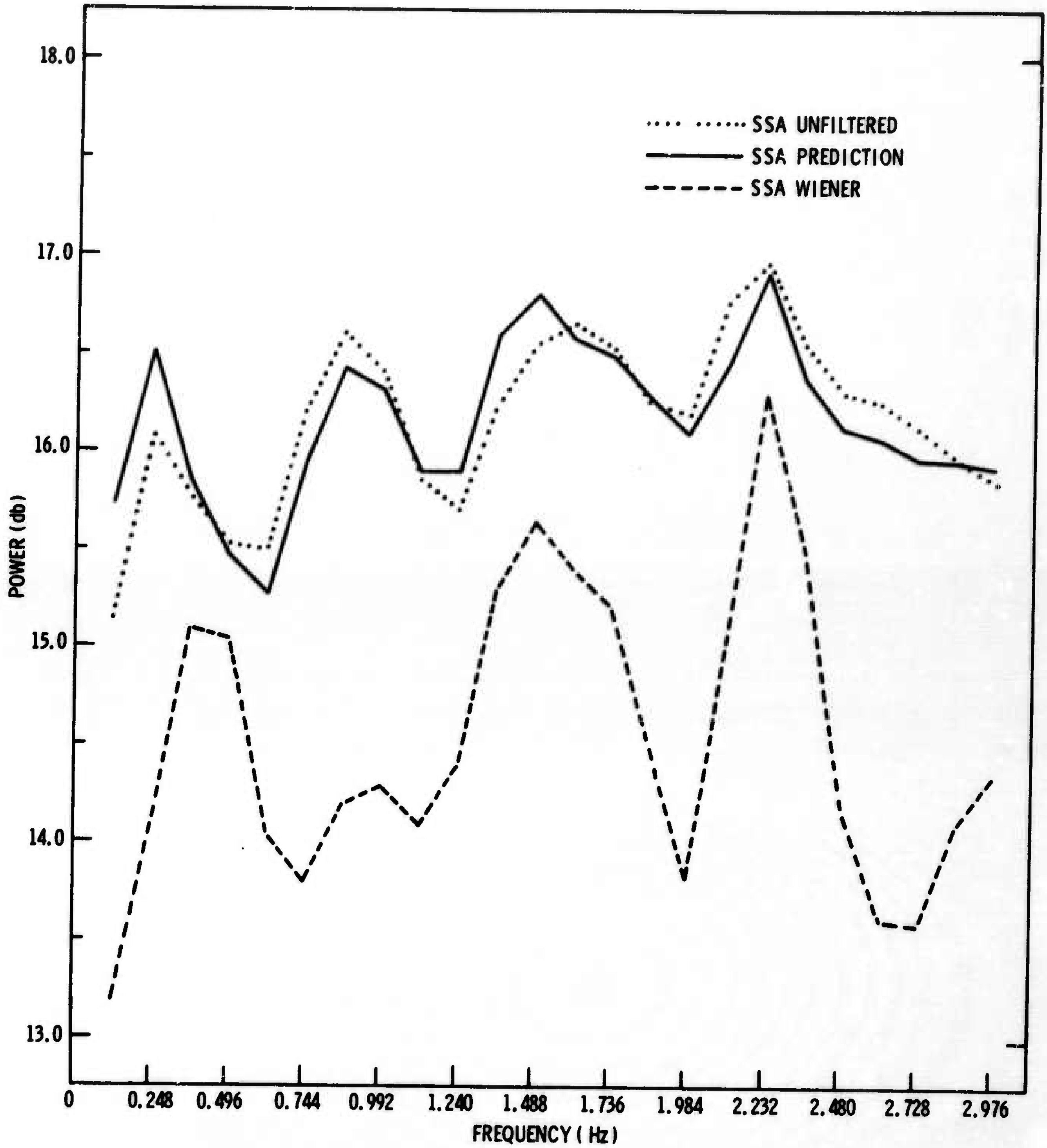

Figure 6. Power Spectra of SSA: Unfiltered, Wiener Output, and Adaptive Prediction Error

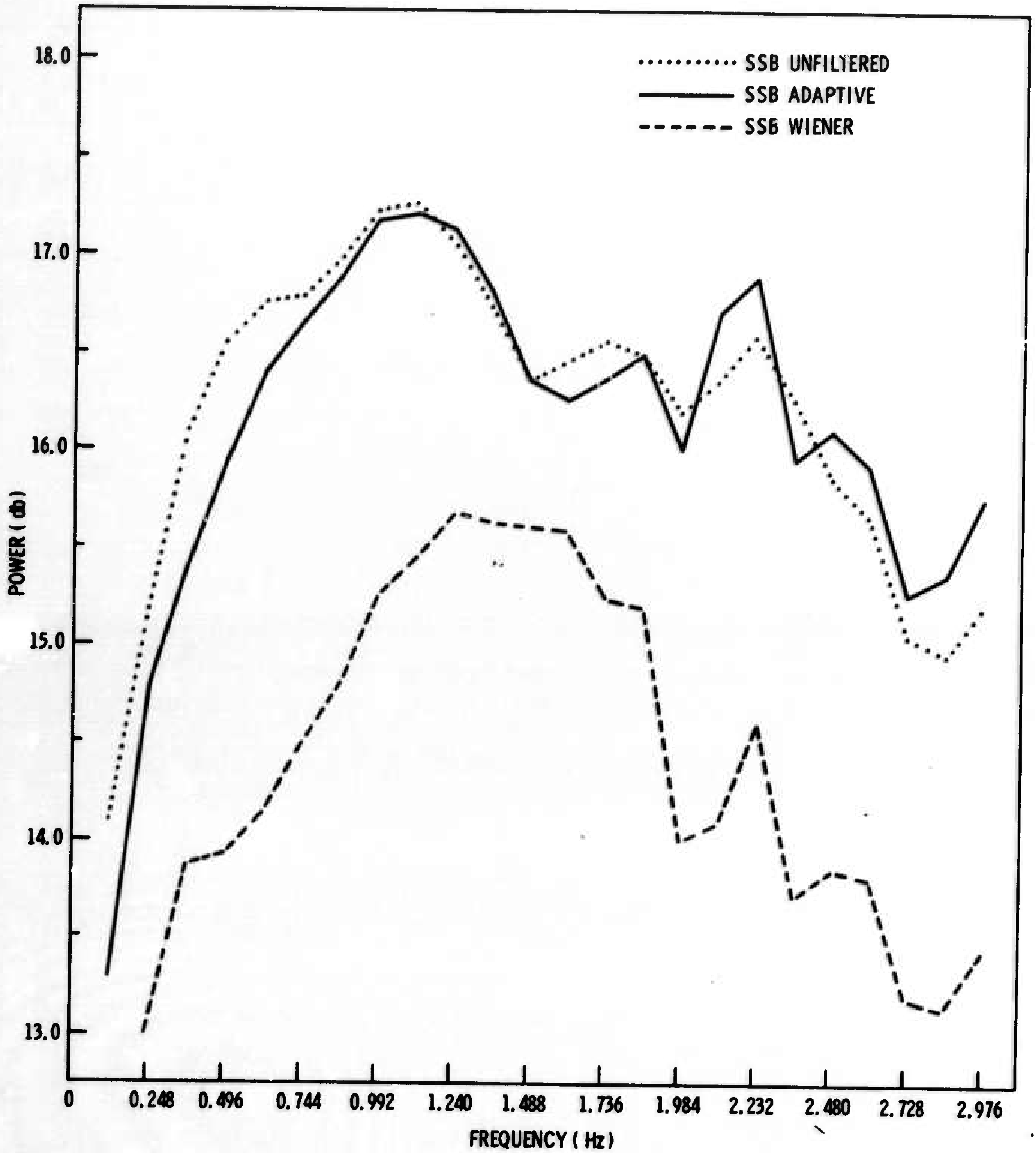

Figure 7. Power Spectra of SSB: Unfiltered, Wiener Output, and Adaptive Prediction Error

Power spectra of the adaptively filtered SSA and SSB showed no attenuation compared to unfiltered signals. On the other hand, spectra of the Wiener output of SSA and SSB showed an attenuation of 1 to 2 db.

Before designing the filters, the adaptive program multiplied all traces by a constant chosen to give unit variance to the vertical seismometer trace. As the filters were designed and applied to the data, the mean-square prediction error was computed over the entire trace. For NSB, this value was 0.78.

Figure 8, taken from Special Report No. 2, depicts noise component spectra of NS3 collected in 1962.[3] As can be seen, at 0.2 Hz, the P-wave energy was 2 db lower than the surface energy but increased rapidly with increase in frequency and, at 0.4 Hz, became comparable to the contribution from the surface-wave energy. Above 0.4 Hz, the P-wave energy was dominant. At 1.0 Hz, the P-wave energy increased to a level 5 db above the surface energy.

It is difficult for array processors of the type considered here to distinguish between P-wave noise and P-wave signal. The noise analysis of Figure 8 could not be performed above 1.0 Hz because, at the higher frequencies, wavelengths were sufficiently small to interfere with the inhomogeneous geology of WMO and gave highly disorganized, uninterpretable spectra. Although a detailed analysis of the noise at higher frequencies is not available, there are definite indications that, above 1.0 Hz, the surface-wave energy dominates the P-wave energy.

Figure 9 shows the result of a previous study which designed a multichannel processor from NS3 using a 10-element array of vertical seismometers.[4] From this figure, an examination of the signal-to-noise improvement and the f-$\vec{k}$ response of the processor at 1.8 Hz indicates that, at 1.8 Hz, the major concentration of the energy lies in the surface-wave region.

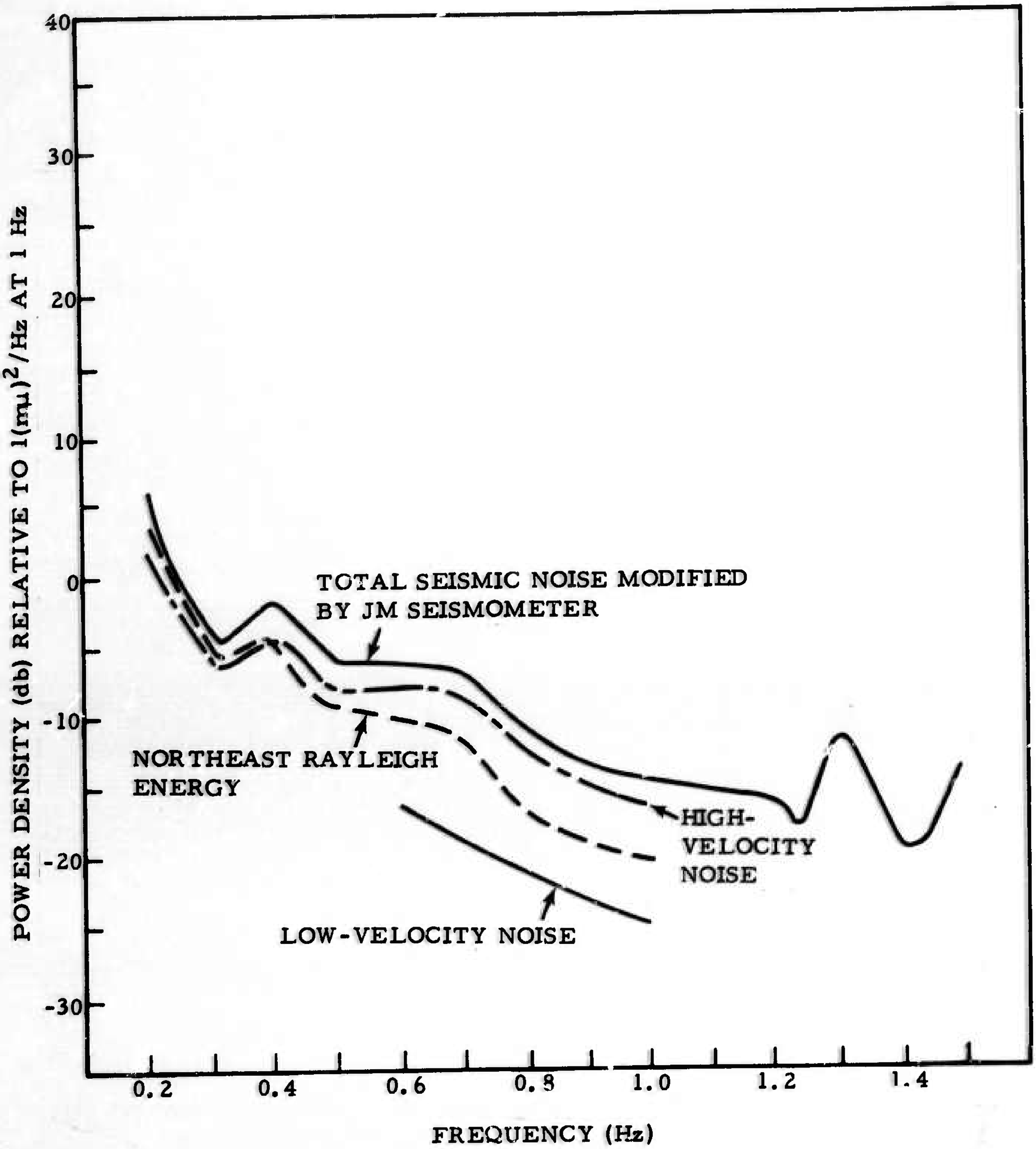

Figure 8. Absolute Frequency Power-Density Spectra for Three Noise Components in WMO Noise Sample 3

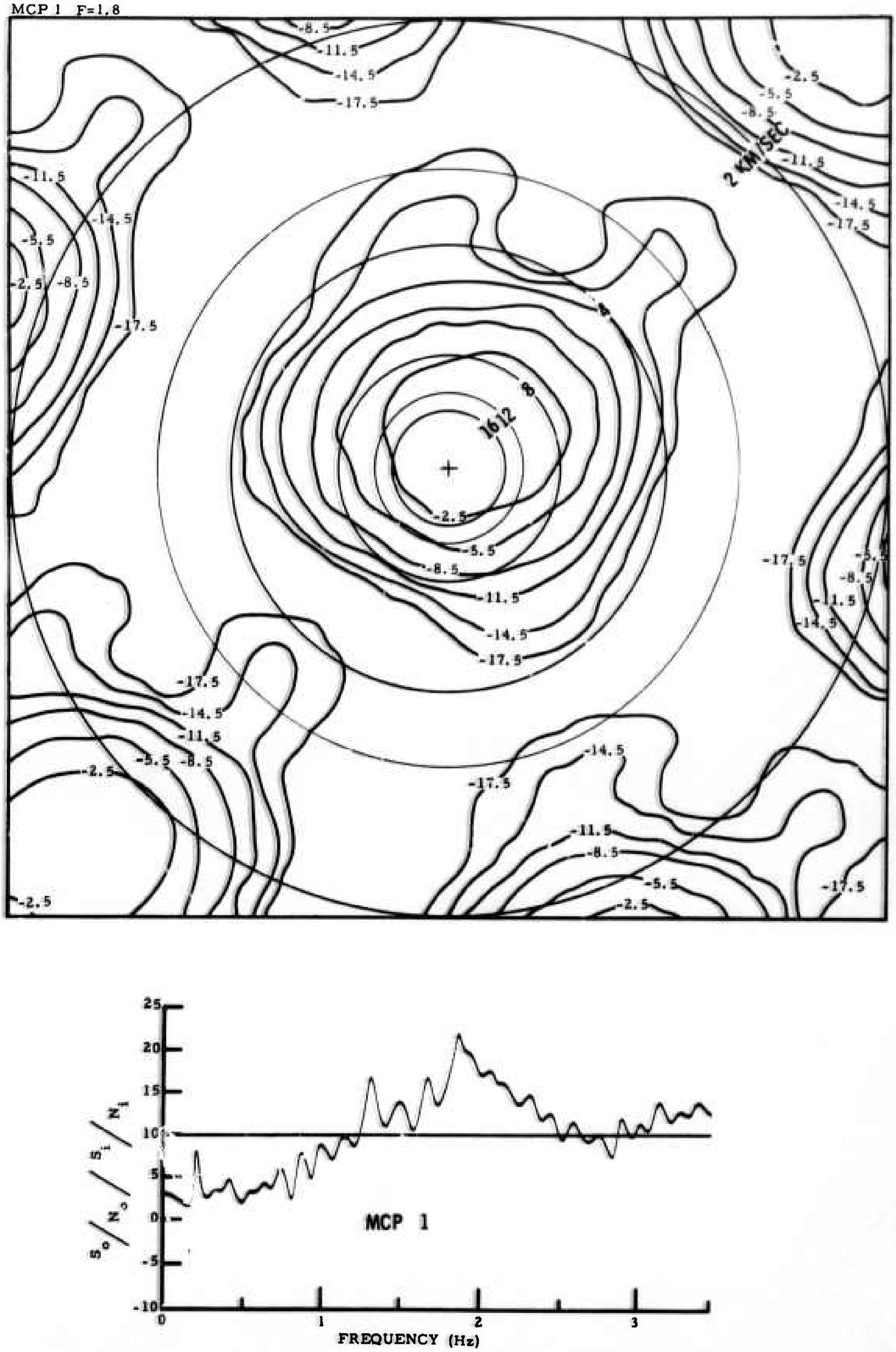

Figure 9. K-Plane Responses (db) for MCP 1 (at F = 1.8) and SNR Improvement of NS3 Using MCP 1

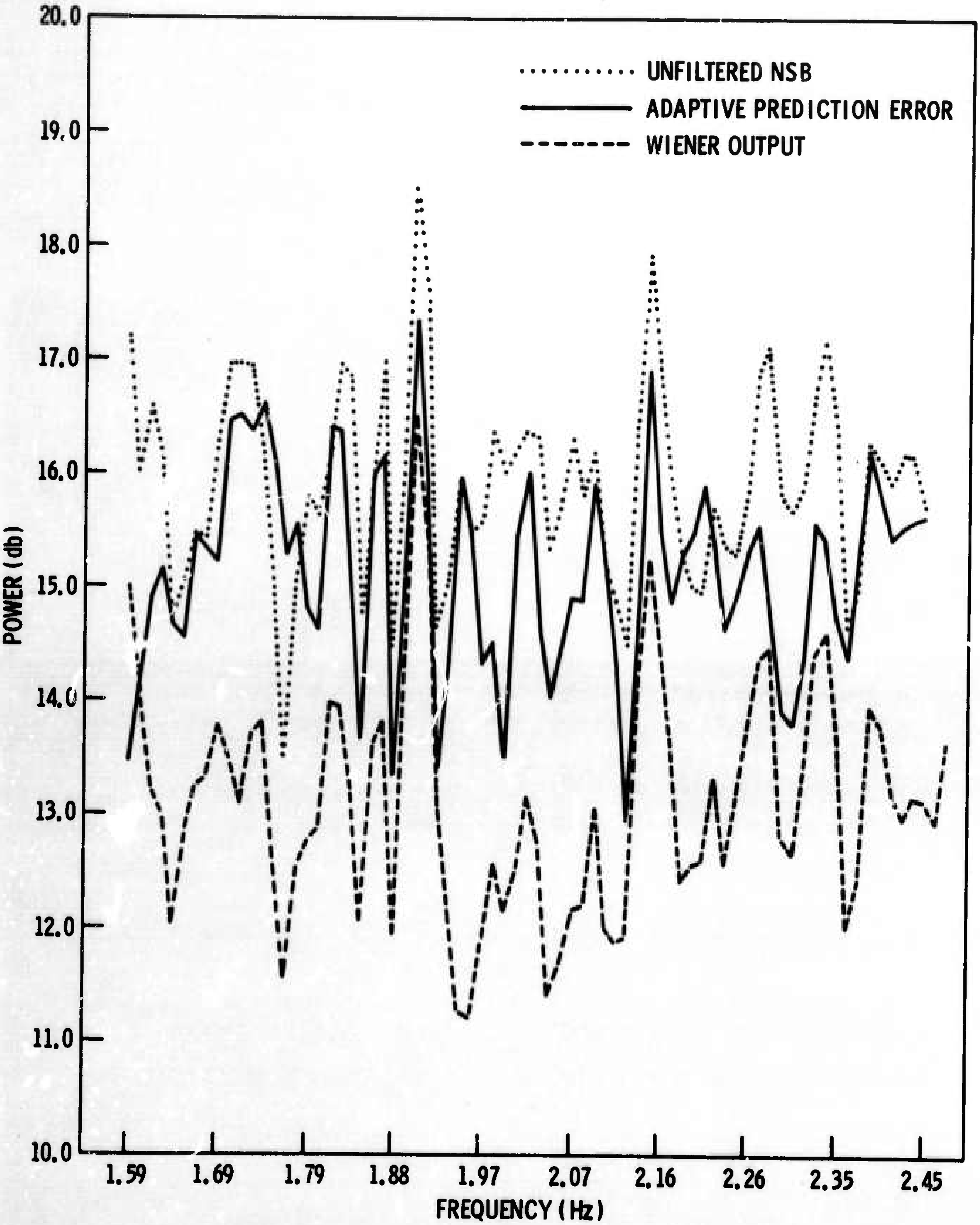

Figure 10. High-Resolution Power Spectra of NSB in Vicinity of 2.0 Hz: Unfiltered, Wiener Output, and Adaptive Prediction Error

The inability of the processors to reject this surface-wave noise is surprising. Examination of the horizontal-seismometer noise recordings shows a disturbing amount of dissimilarity between traces and along a number of the individual traces. This fact, coupled with the poor results obtained, suggests that the data may be seriously contaminated by random nonseismic noise.

Noise spectra presented thus far were obtained by computing the Fourier transforms of the autocorrelation functions with 24 nonzero lags. Higher-resolution spectra of the time traces of filtered and unfiltered NSB were also computed by taking the Fourier transforms of the autocorrelation functions for 249 nonzero lags. The 2.0-Hz peak in the low-resolution spectrum appears to consist of two separate peaks at 1.90 Hz and 2.15 Hz in the higher-resolution spectrum. Figure 10 presents a portion of this high-resolution spectrum in the vicinity of 2.0 Hz. These two peaks are only about 2 to 3 db higher than other peaks in that vicinity; hence, the resolution of the 2.0 Hz into these two peaks should not be overemphasized.

C. ABSOLUTE SPECTRUM

The absolute level of the NS3 collected at WMO in 1962 (previously published[3]) has been questioned as a result of uncertainties in the calibration records. NSB is recent and, although the experimental horizontal-seismometer array seems to be seriously contaminated by random noise, the permanent shallow-buried array (U_1 - U_{13}) appears to be uncontaminated.

To compute the power spectrum of NSB in absolute units relative to actual ground motion was therefore considered appropriate. The power spectrum of NSB, as recorded by the shallow-buried vertical seismometer U_3, was computed and corrected for the frequency response of the seismometer. This power spectrum showed close agreement to power spectra obtained from two other shallow-buried seismometers, U_7 and U_9. Figure 11 shows the absolute power spectra with and without corrections for the frequency response of the seismometer.

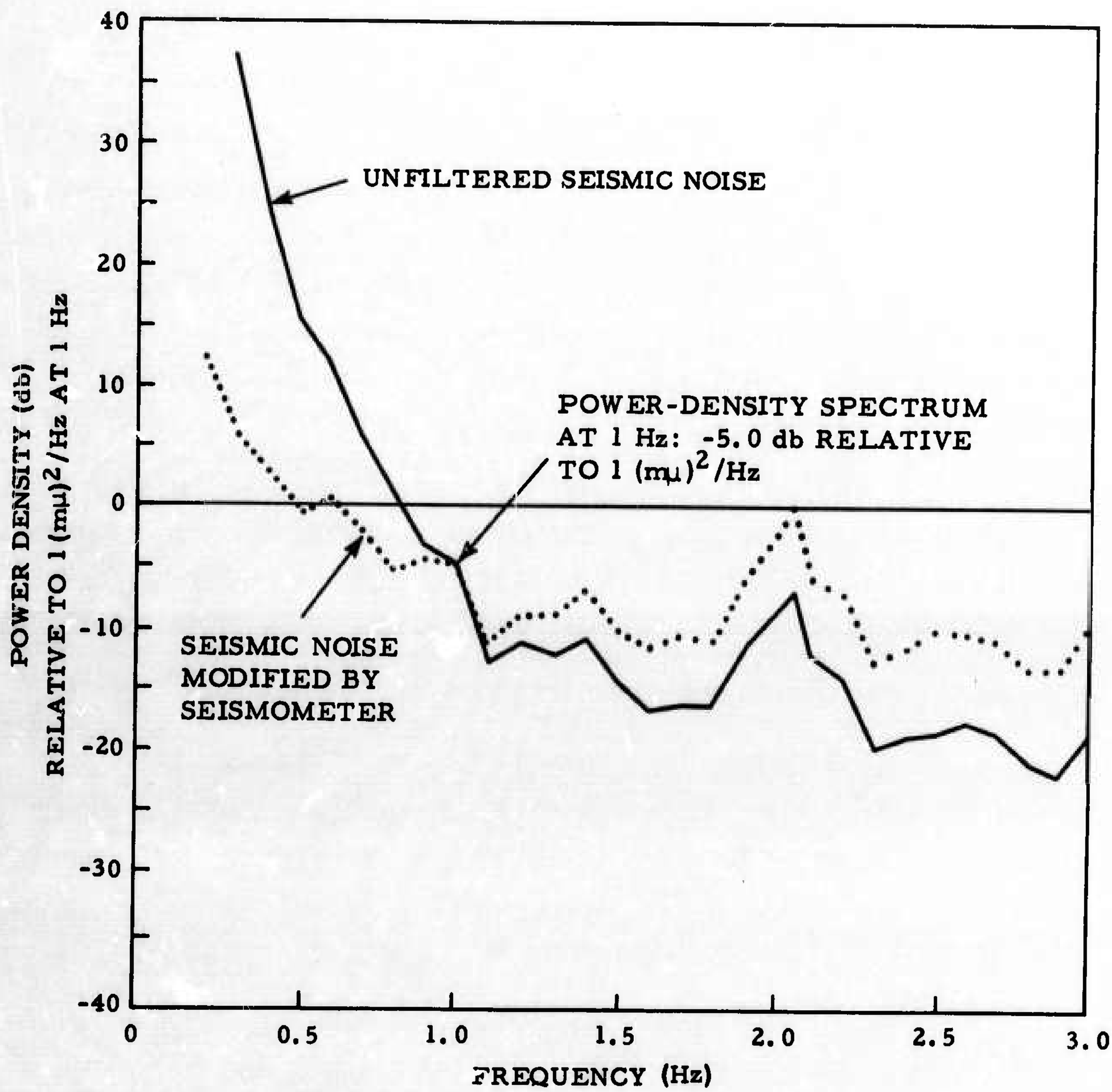

Figure 11. Absolute Power-Density Spectra of NSB as Seen by Shallow-Hole Seismometer

The absolute spectrum of NS3, when compared with the spectrum of the TFO long-noise sample,[5] was found to be lower than the TFC spectrum. Reliability of the NS3 spectrum, therefore, was questionable because the noisier WMO site was expected to show a higher spectrum than TFO. The NSB spectrum showed a higher value when compared with the TFO spectrum, as would be expected. A noticeable hump in NS3 at 0.4 Hz also could not be explained.[3] A hump near 0.5 Hz can be seen in the spectrum of NSB. Whether this hump, which is not too pronounced, was caused by something physically real or was simply a statistical behavior of the curve is difficult to say. For convenience, the NS3 spectrum from the previous report[3] and the spectrum of the TFO long-noise sample[5] are reproduced in Figures 12 and 13.

D. SPECTRA OF NSB AS SEEN BY TWO MUTUALLY PERPENDICULAR HORIZONTAL SEISMOMETERS

The power spectra of NSB, as recorded by the seismometers H_4 (pointing toward the lakes in the northeast) and H_9 (aligned in a direction perpendicular to H_4) have been computed also (Figure 14) to examine the directionality of the noise.

Note that the 2.0-Hz peak is not apparent in the spectrum of the seismometer which pointed in the direction of the lake but is very prominent on the other seismometer.

The gains of the two seismometers were equalized to give a direct comparison between the two spectra.

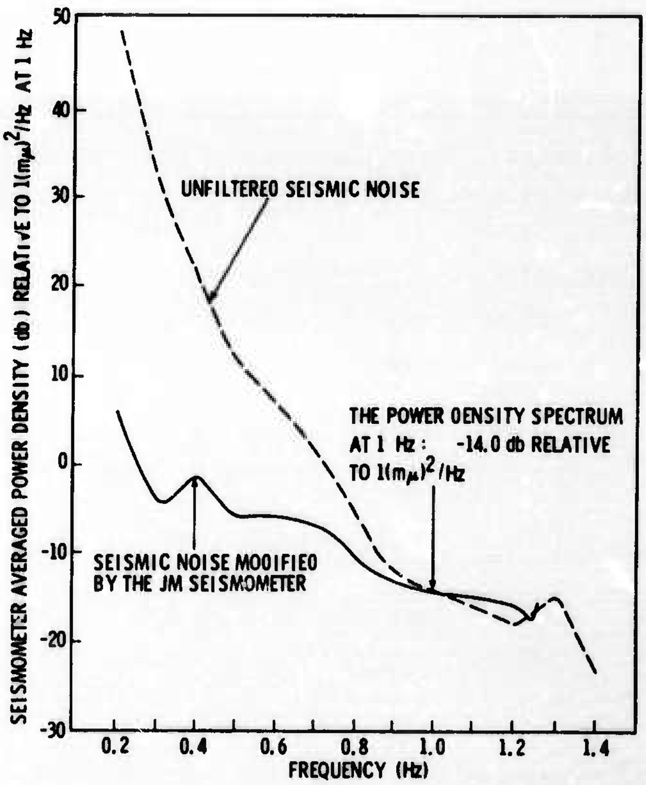

Figure 12. Absolute Power-Density Spectra of NS3

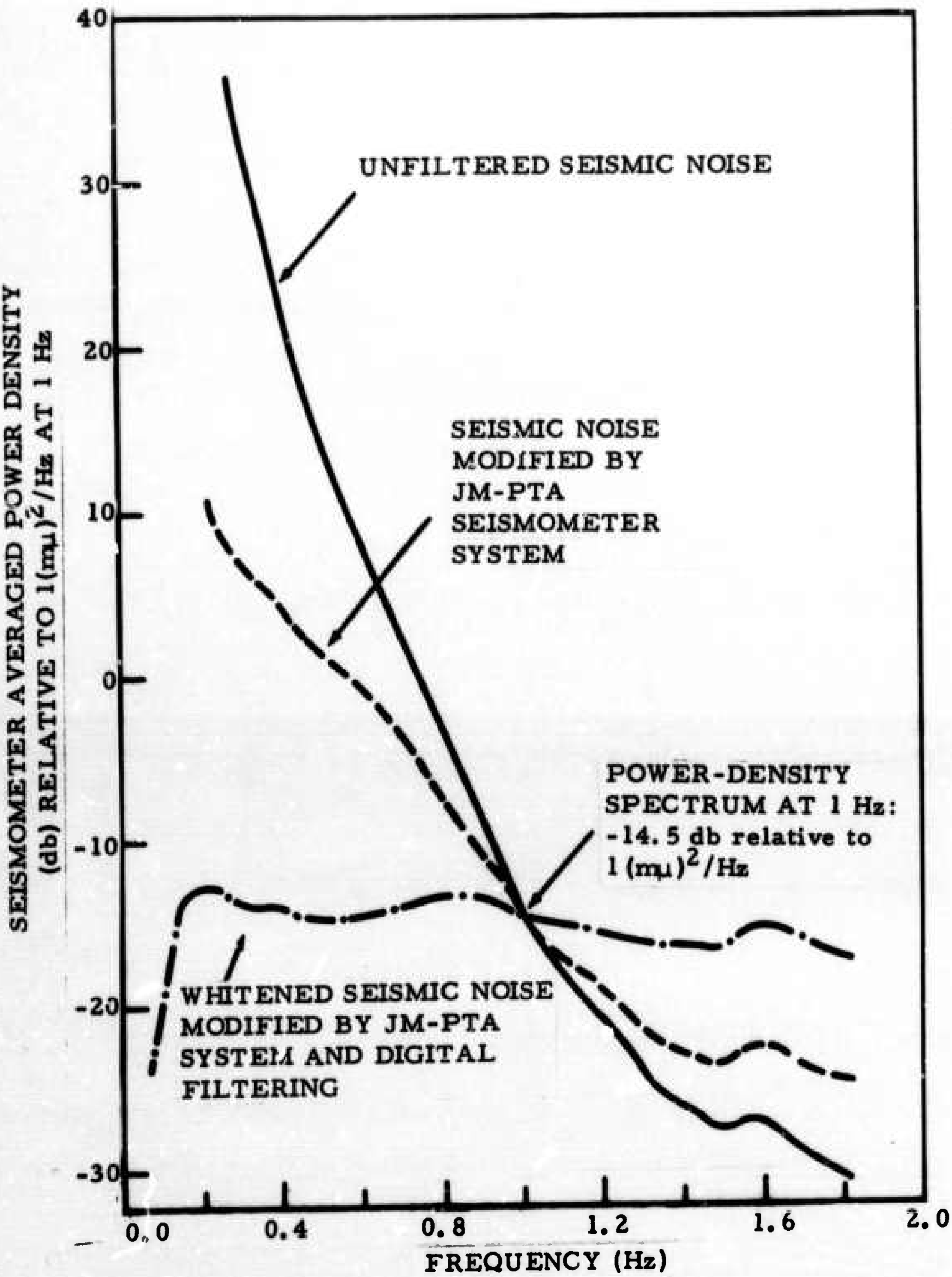

Figure 13. 21-Seismometer Averaged Absolute Power-Density Spectra

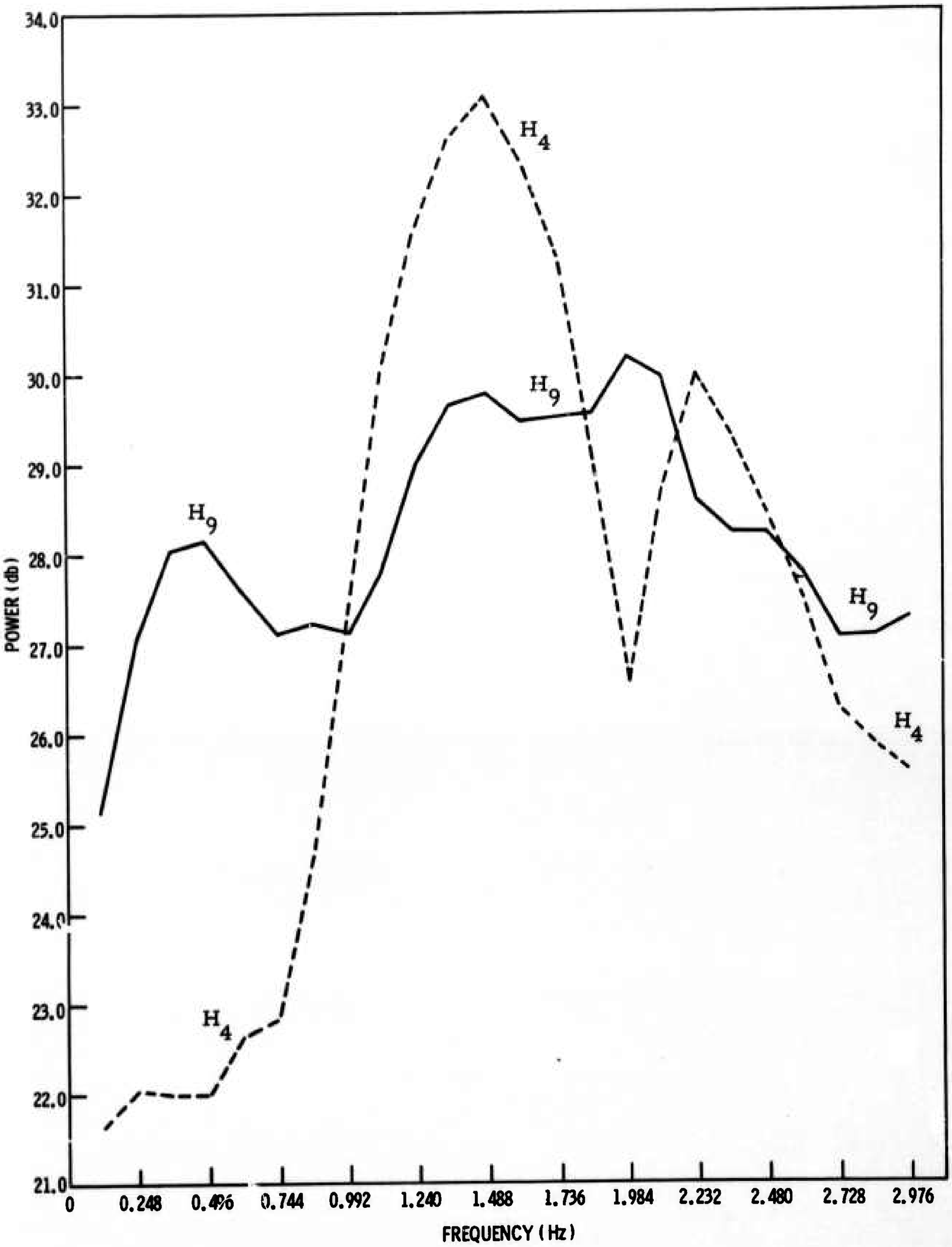

Figure 14. Spectra of NSB as Recorded by H_4 and H_9

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

The multichannel filters evaluated in this experiment were designed to predict the noise component of the vertical seismometer trace using the data recorded by the horizontal seismometers. The results obtained indicate that such processing, when used in this way, can provide only very limited enhancement of P-wave signals at WMO. This indication is inconsistent with previous theoretical work.

The poor performance of the multichannel filters below 1.0 Hz was expected, since the dominant P-wave noise cannot be effectively suppressed by this type of processing. The noise above 1.0 Hz was mainly Rayleigh-wave energy, however, and substantial signal-to-noise improvement should be achievable.

The horizontal-seismometer noise recordings used in the experiment showed considerable dissimilarity between traces and along a number of the individual traces. This fact, coupled with the poor results obtained, indicates that the data may be seriously contaminated by random nonseismic noise. Consequently, these results cannot be regarded as conclusive.

Obtained during the data recording period was one 30-min noise sample which appeared visually to be relatively free of the irregularity just mentioned. Due to the lack of usable events occurring on the same day, this noise sample was not processed. Now, it appears, this sample may be very useful for gaining a better understanding of the performance of the experimental array. Detailed analysis of this noise sample will be directed to a more complete understanding of the noise field as seen by the horizontal and vertical seismometers. Obvious recording errors such as spikes will be corrected. Power-density spectra will be used to study the noise-level differences between seismometers. The nature of the 2-Hz spectral lines will be examined with the aid of high-resolution power-density spectra and narrowband recursive filters. Data recorded simultaneously from most of the elements of the permanent shallow-buried WMO array will be used where appropriate in this evaluation.

Guided by the results, a careful analysis of the crosspower spectral matrix of the experimental array will be made. This detailed investigation will yield a more definitive assessment of horizontal-vertical interpolation arrays than has been achieved to date.

SECTION V

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(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Texas Instruments Incorporated Science Services Division P.O. Box 5621, Dallas, Texas 75222	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP —

3. REPORT TITLE
SIGNAL ENHANCEMENT WITH AN ARRAY OF VERTICAL AND HORIZONTAL SEISMOMETERS — ADVANCED ARRAY RESEARCH — SPECIAL REPORT NO. 11

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Special

5. AUTHOR(S) (Last name, first name, initial)
Heiting, Leo N.
Rizvi, Syed A.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
28 February 1968	30	5

8a. CONTRACT OR GRANT NO. Contract F33657-67-C-0708-P001 b. PROJECT NO. VELA T/7701 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) — 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) —

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