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# INVESTIGATION OF SHORT-PERIOD SEISMIC NOISE IN MAJOR PHYSIOGRAPHIC ENVIRONMENTS OF CONTINENTAL UNITED STATES

G. E. Frantti
Institute of Science and Technology
The University of Michigan
Ann Arbor, Michigan

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Final Report
Period Covered: September 1, 1961
Through December 31, 1964

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Report No. 4711-22-F/5178-47-T

June 1965



Prepared
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AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS

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## ACKNOWLEDGMENTS

The author expresses appreciation to Dr. James T. Wilson for contributions, particularly in early phases of the study, and to David E. Willis, under whose direction many of the supporting field programs were conducted.

Instrumentation designs and modifications necessary for making field measurements and laboratory frequency analyses were accomplished under the direction of Harry J. Bugajski.

Various members of the Geophysics Laboratory are thanked for their assistance in data analysis.

The cooperation of The Geotechnical Corporation in making available some of the data used in the contour map of Fig. 7 is appreciated.

## FOREWORD

For several years research in seismology has been in progress at the Geophysics Laboratory of The University of Michigan's Institute of Science and Technology, through the sponsorship of such agencies as the U. S. Air Force Office of Scientific Research, Air Force Technical Applications Center, Air Force Cambridge Research Laboratories, and National Science Foundation. Field programs reaching major regions of the United States and certain non-North American locations have provided the laboratory a library of recordings of seismic signals and earth noise. In this report, recordings of the latter are used to investigate variations of short-period earth noise in physiographic environments of the continental United States.

The report summarizes three years of study, ending 31 December 1964, sponsored by the Air Force Cambridge Research Laboratories under Contract AF 19(628)-200 as part of the Advanced Research Projects Agency's VELA UNIFORM program. Acknowledgments are also made to the agencies mentioned above, whose contracts made possible the research which provided many of the field measurements.

This report is prepared as a final report under Contract AF 19(628)-200 and as a technical report under Contract AF 49(638)-1170.

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## ABSTRACT

Measurements of spectral density levels of short-period seismic noise are obtained for points distributed throughout the continental United States and for a few non-North American locations. Noise amplitudes and gradients in the far field correlate on a regional basis with major physiographic provinces, as revealed by iso-particle-velocity contouring. The ensemble of space and time samples of noise is examined to illustrate the average spectrum and dispersion for three orthogonal components of ground-particle velocity in the range 0.25 to 100 cps. Probability distributions of noise amplitudes based on a collection of space averages and time averages are presented for several frequencies. The ratio of horizontal to vertical noise amplitude (H/Z) exceeds the theoretical value for simple Rayleigh waves and shows a frequency-dependent variation with regional geologic environment.

## CONTENTS

## FIGURES

# INVESTIGATION OF SHORT-PERIOD SEISMIC NOISE IN MAJOR PHYSIOGRAPHIC ENVIRONMENTS OF CONTINENTAL UNITED STATES

## 1 INTRODUCTION

A review of seismological literature, with reference to the seismic noise of the earth's surface, revealed that it would be informative to investigate the variation of noise with regional physiographic environment and to obtain additional observational data describing the "average" noise spectrum. Such an investigation can best be conducted by collecting numerous measurements at many different locations, using consistent recording and analyzing instruments.

After years of seismological research, such a set of field data has been gathered at the Geophysics Laboratory of The University of Michigan's Institute of Science and Technology. In this report we analyze noise signatures, in the frequency range 0.25 to 100 cps, obtained primarily throughout the continental United States but include some observations for scattered non-North American sites.

Because we are using recordings obtained from a number of separate field projects, and because of their geographical distribution, the data are not in general ideal, but are considered adequate for the study. The ensemble of noise measurements consists of a collection of short-time samples obtained at random times from sites sufficiently widespread to include the major physiographic provinces of the continental United States. Greatest station density occurs in the western Great Lakes, upper Mississippi embayment, central and southern Appalachians, and the southeastern Basin and Range regions. Scattered (less densely spaced) measurements are available for the northern and central Rocky Mountains, central and southern interior plains, and southeastern coastal plains. The data are supplemented throughout various regions by measurements which were kindly made available by The Geotechnical Corporation [1] and which were used in preparing Fig. 7.

We consider the spatial fluctuation of natural short-period seismic noise to be the differences in spectral densities measured at the earth's surface in multiple locations. The seismometers were buried just below ground level to reduce local effects. While it might be desirable to use the mean value of spectral amplitudes at specific sites, data describing the mean are not available for many space stations. Thus, except for the sites where multiple observations are available, spectral amplitudes are obtained from one 2-min time sample selected as representative of the noise signature. These samples were selected during time periods that appeared to be free from obvious, local, anomalous sources of noise, near the site at the time of recording.

## 2
## DISCUSSION AND RESULTS

### 2.1. INSTRUMENTATION

Three component seismometers and Ampex FM magnetic tape recorders (CP 100 and 351 models) were used in the field recording. Early in the program 1-sec Willmore and Benioff seismometers were employed. Later 2-cycle Hall Sears (HS-10) geophones with 210,000-ohm coils were packaged into one unit and a majority of the measurements were subsequently obtained with that unit. Average response curves comparing these seismometers are shown in Fig. 1. The roll-off of the HS-10 response at low frequencies very nearly matches the inverse of the seismic noise amplitude spectrum at corresponding periods. Late in the program a capacitor was used across the 2-cycle geophone to roll-off the response above 10 cps in situations where this was desirable. The seismic preamplifier essentially has a flat response over the frequency range of interest (3 db down points 0.5 and 800 cps). An average noise curve for The University of Michigan's unmodified transistor amplifier is shown in Fig. 2 in terms of equivalent ground motion. The amplifier noise level at 1 cps is of the same order of magnitude as seismometer noise at 1 cps as calculated by Byrne [2] for a 1-sec Benioff and as determined by Jackson [3] who generalized the work of Byrne to include vane or viscous damping. Figure 3 illustrates the equipment typically used at a field recording station.

### 2.2. DATA ANALYSIS

Wideband magnetic tapes from the field are analyzed in the laboratory with either Krohn-hite-variable passband filters or 1/3-octave polyfilters. Noise measurements are then made from the filtered records. Peak-to-peak velocity amplitudes, computed for each 1/3-octave frequency, are based on the envelope of the wave trace on the filtered seismogram; specifically, the amplitudes of the crests of the envelope are averaged over a continuous 2 min interval and the result corrected to true ground velocity.

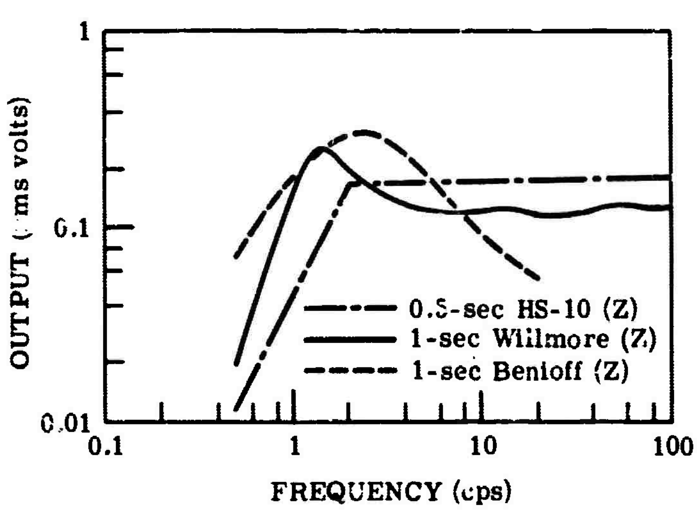


FIGURE 1. COMPARISON OF SEISMOMETER RESPONSES

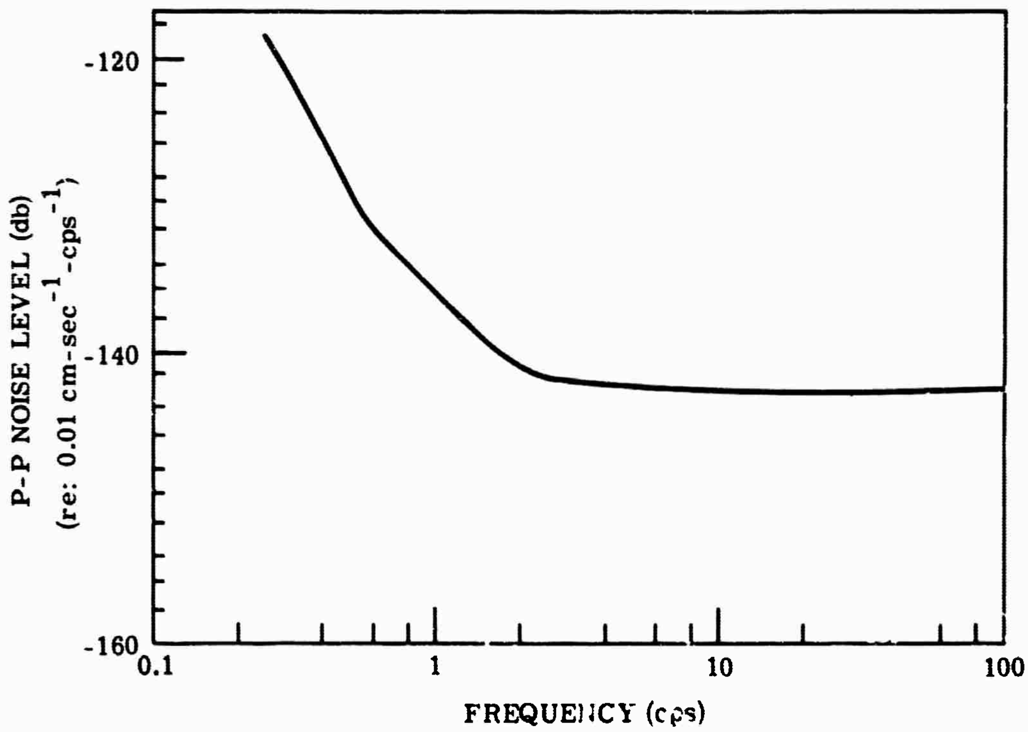


FIGURE 2. AVERAGE NOISE CURVE FOR SEISMIC PREAMPLIFIERS

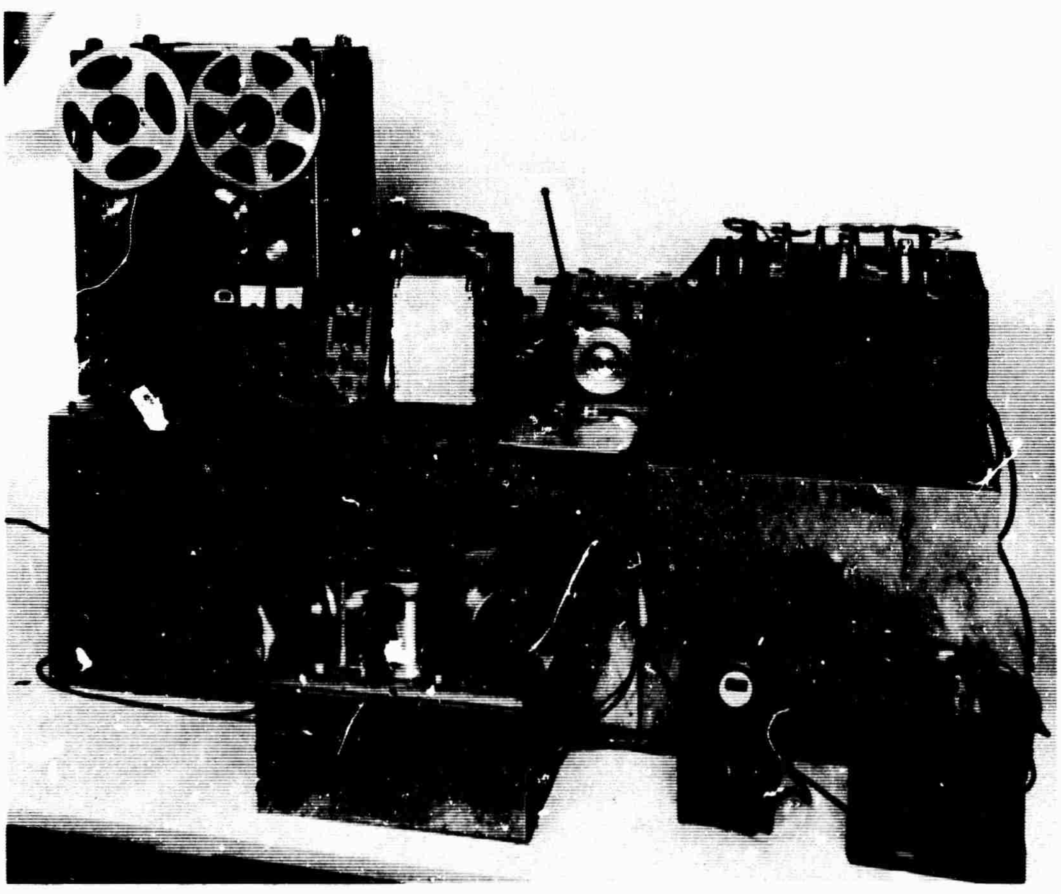

FIGURE 3. TYPICAL SEISMIC FIELD EQUIPMENT

Many individuals read seismograms during the course of the study. Results between individuals correlated within 2 db. Many of the filtered noise samples were analyzed with a Model 302B Ballantine rms averaging meter, a Model 310A true rms meter, and by detailed computation of the rms signal level. A comparison of these results showed that the general averaging technique used throughout the program always gives results higher than the true rms. The difference varied from about 2 1/2 db to a maximum of 6 db. We conclude from this that our results, being a good estimate of the shape of the rms spectra and a crude estimate of the rms signal level (the latter is on the average about 4 1/2 db lower), lead to reasonable approximations of noise power. An important advantage of the averaging technique used is that it ignores artifacts, such as transients due to tape dropouts, in the sample interval.

## 2.3. AVERAGE NOISE SPECTRUM

Amplitude distributions were constructed for the entire noise sample and found to be skewed-right, in part a consequence of the fact that the amplitudes are bounded by zero on the low end. The mean of such a group of averages is affected in a pronounced way by a relatively small number of samples on the extreme high side. Therefore, in using the ensemble averages to obtain the "average" noise spectrum, we consider, because of the skewness, that the median is more significant than the mean. In Fig. 4, 5, and 6 then, are shown the medians determined for three orthogonal components of ground velocity; namely, vertical (Z), N-S horizontal, and E-W horizontal respectively. The spectral shapes reasonably reflect the expected results for short-period noise, except possibly for the anomalous decrease in level near 100 cps. The first and third quartile points shown indicate the amount of dispersion in the data, and the maximum and minimum lines outline the range which includes 98% of the data. The three medians are similar and within a few db of each other. The interquartile distance is about 8 db at 0.25 cps and increases with increasing frequency, indicating greater standard deviation in the data at higher frequencies.

## 2.4. GEOGRAPHICAL VARIATION OF NOISE

Figures 13 through 22 included in the appendix show three-component spectra for nine sites in each of nine broad continental areas and for six sites scattered outside of North America. Additional spectra have previously been published [4 and 5]. Characteristics of individual measurements can be examined from these graphs in the frequency range 0.5 to 31.5 cps. For example note that:

(a) There is a strong contribution to the noise spectrum centered near 1 cps and in the approximate band 0.6 to 1.6 cps associated with the Great Lakes and emphasized at sites on relatively unconsolidated earth materials.

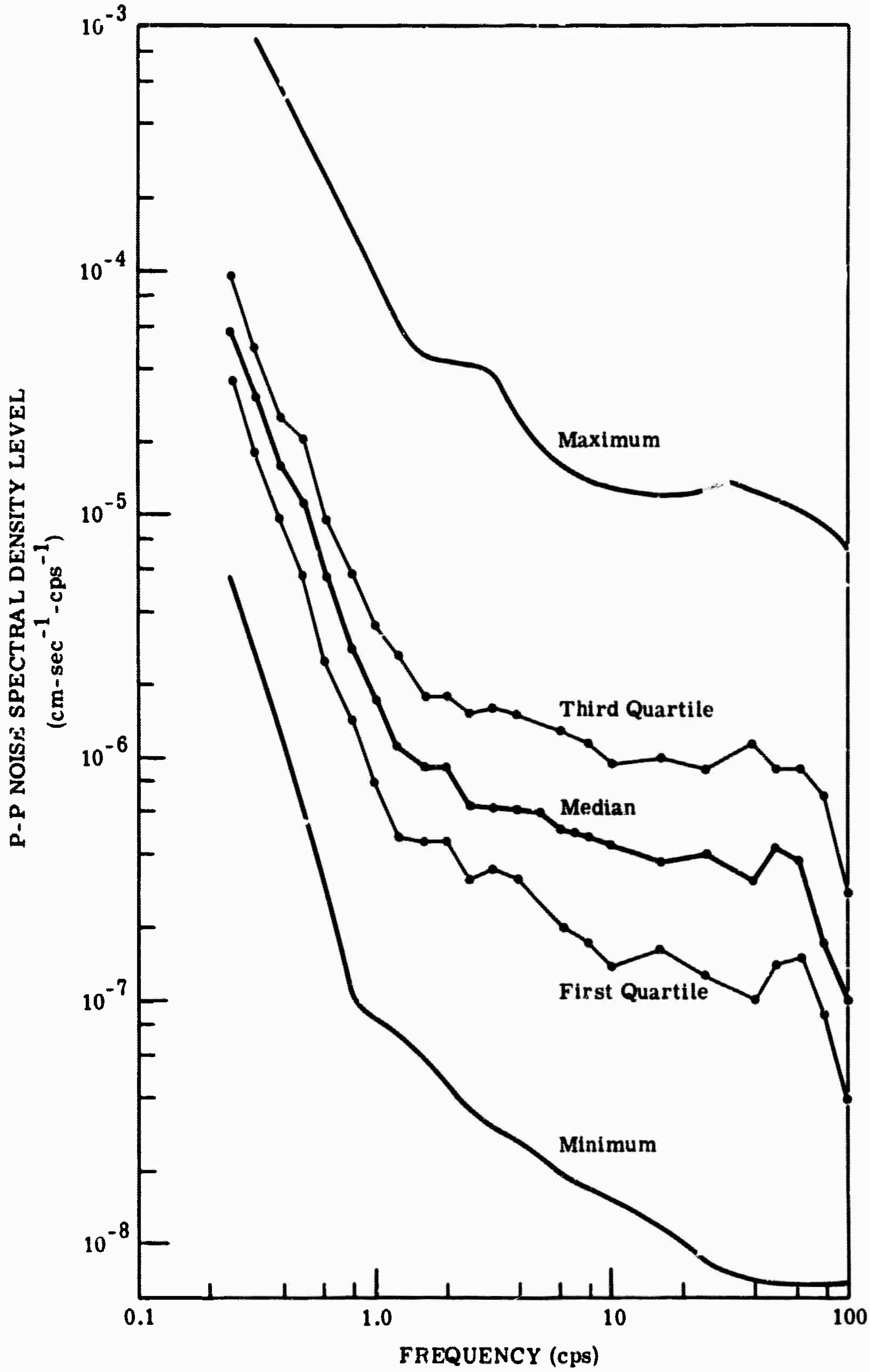


FIGURE 4. MEDIAN, QUARTILES, AND RANGE OF ENSEMBLE AVERAGES (Z)

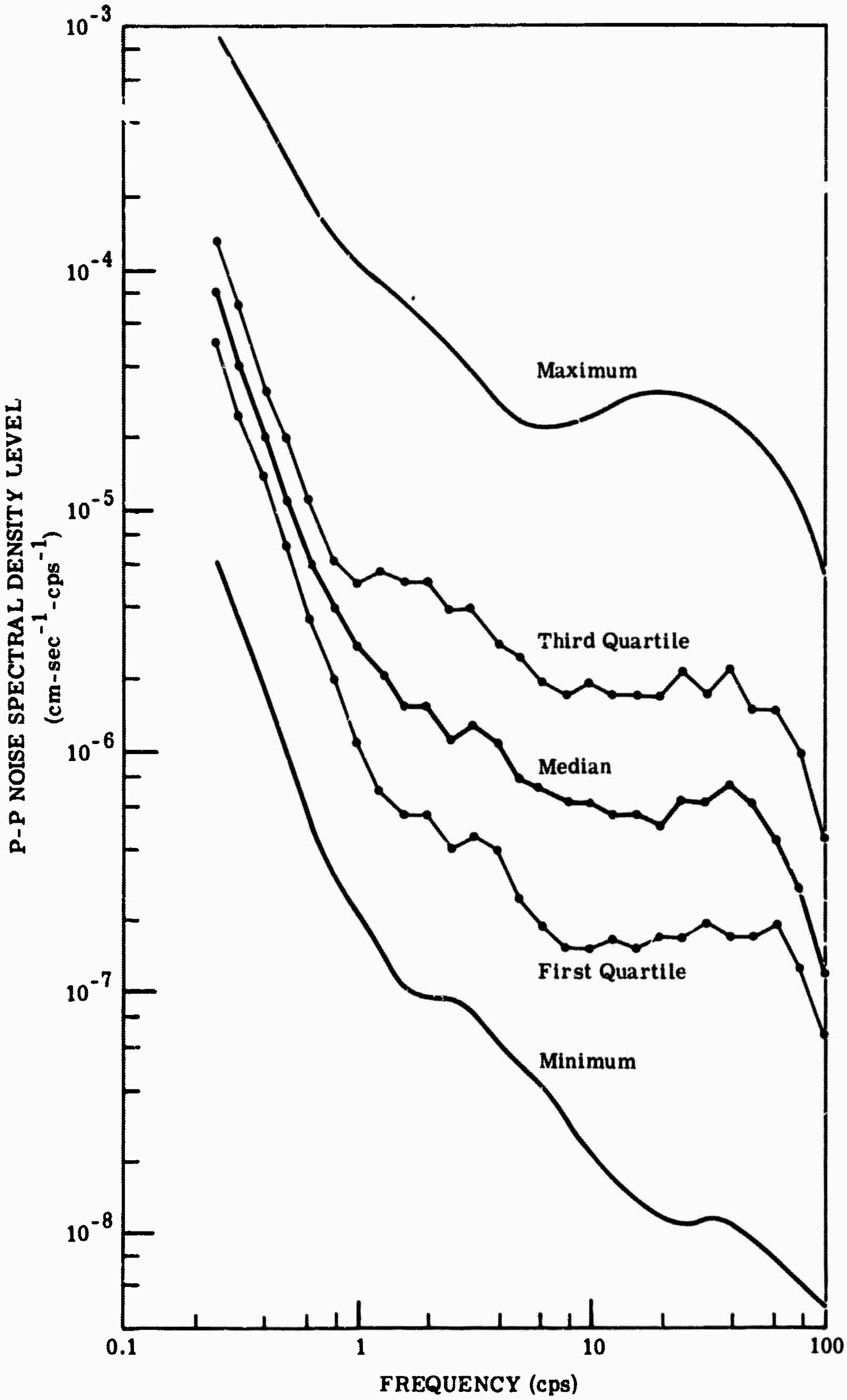


FIGURE 5. MEDIAN, QUARTILES, AND RANGE OF ENSEMBLE AVERAGES (t

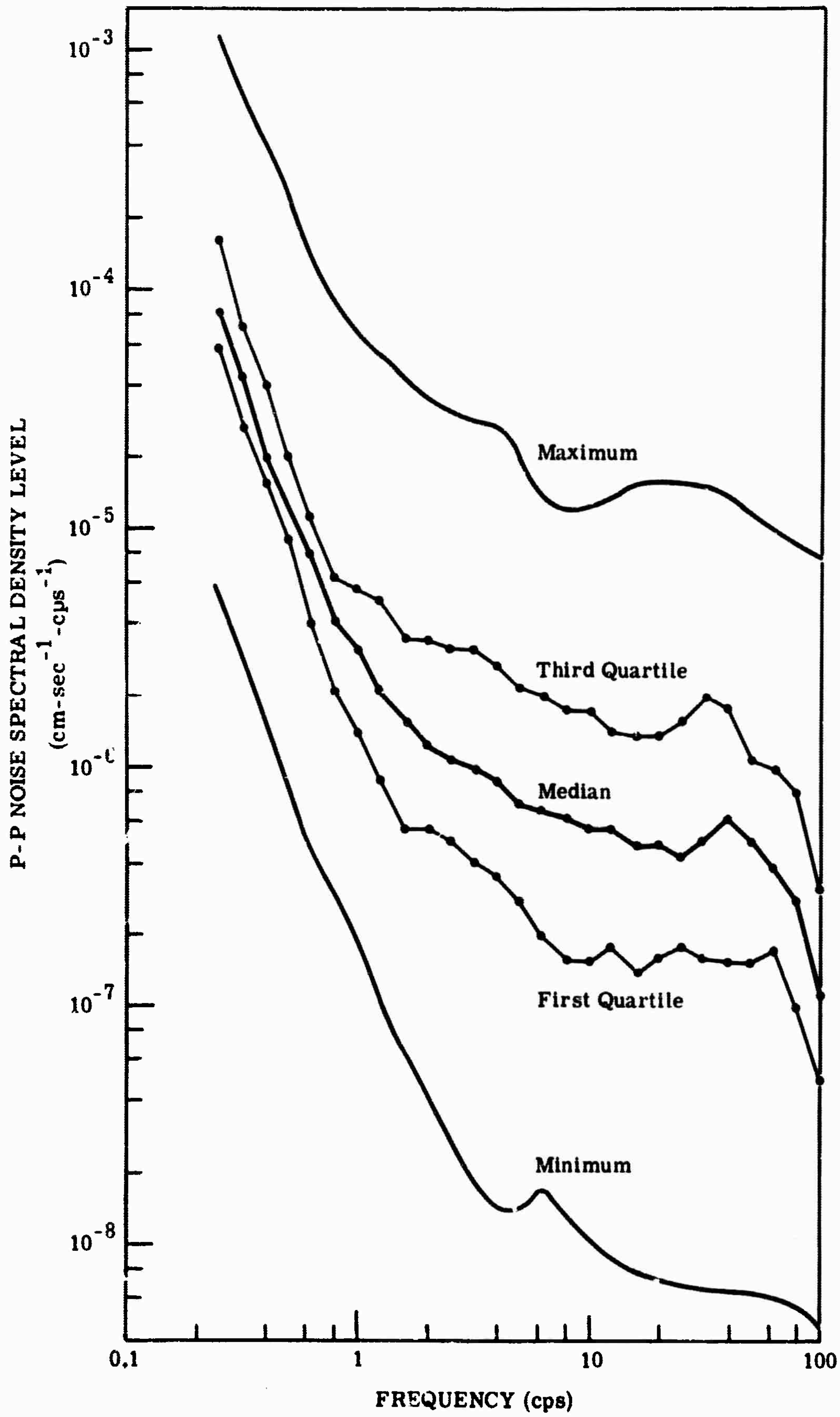


FIGURE 6. MEDIAN, QUARTILES, AND RANGE OF ENSEMBLE AVERAGES (E-W)

(b) There is a variable Q peak in the noise spectrum at or very near 2 cps which is present for many widespread locations.

(c) There is a very positive contribution to the noise spectrum between about 2 and 8 cps for the sites near industrial and cultural complexes.

(d) There is a pronounced rise in the noise spectrum, emphasized above 10 cps, for sites characterized by winds and particularly where unconsolidated geologic materials are involved.

Since exploration of the variation of noise with geography (the primary purpose of this report) from separate displays of spectra is difficult, an alternative technique has been developed. This technique calls for mapping values of ground particle velocity for discrete frequencies and contouring the results two-dimensionally at equivelocity levels, which reveal patterns in the absolute field and in the field gradients. In this form the noise spectral data are more readily compared with physiography. Figures 7a and 7b show the contour pattern for the vertical component at 1 cps and its correlation with physiographic provinces of the continental United States. Figure 7a is supplemented with data of a similar nature supplied by The Geotechnical Corporation whose stations are indicated by stars on the map and whose station values were converted from displacement in millimicrons to velocity in centimeters per second in order to compare with our data. Geotechnical Corporation measurements at 1 cps include a band from 0.3 to 1.4 sec whereas The University of Michigan measurements are for a 1-cycle band centered at 1 cps, but no adjustment was attempted to account for differences in bandwidth.

With reference to Fig. 7, it can be said, in general, that there is a correspondence between the regional physiographic provinces and noise levels. In the west and east there is a general parallel alignment between the particle-velocity contours and the major features of the orogenic belts, such as are found in the Sierras; northern, central, and southern Rockies; and Appalachian Mountains. The correlation is also suggested along the trends of the Ozarks and the Ouachita-Arbuckle-Wichita Mountains in south-central United States. Contour patterns in the Black Hills area of South Dakota and in the Lake Superior Shield area (encompassing surface Pre-Cambrian rock formations) seem to reflect the regional structural features.

The Appalachian Basin, Michigan Basin, Williston Basin of North Dakota, Anadarko Basin of northwestern Oklahoma, and to some extent parts of the Basin and Range Province, all appear to correlate crudely with the particle-velocity contours. Obviously there are some regions within the entire contour space where station density is such that the iso-particle-velocity lines are indeed speculative.

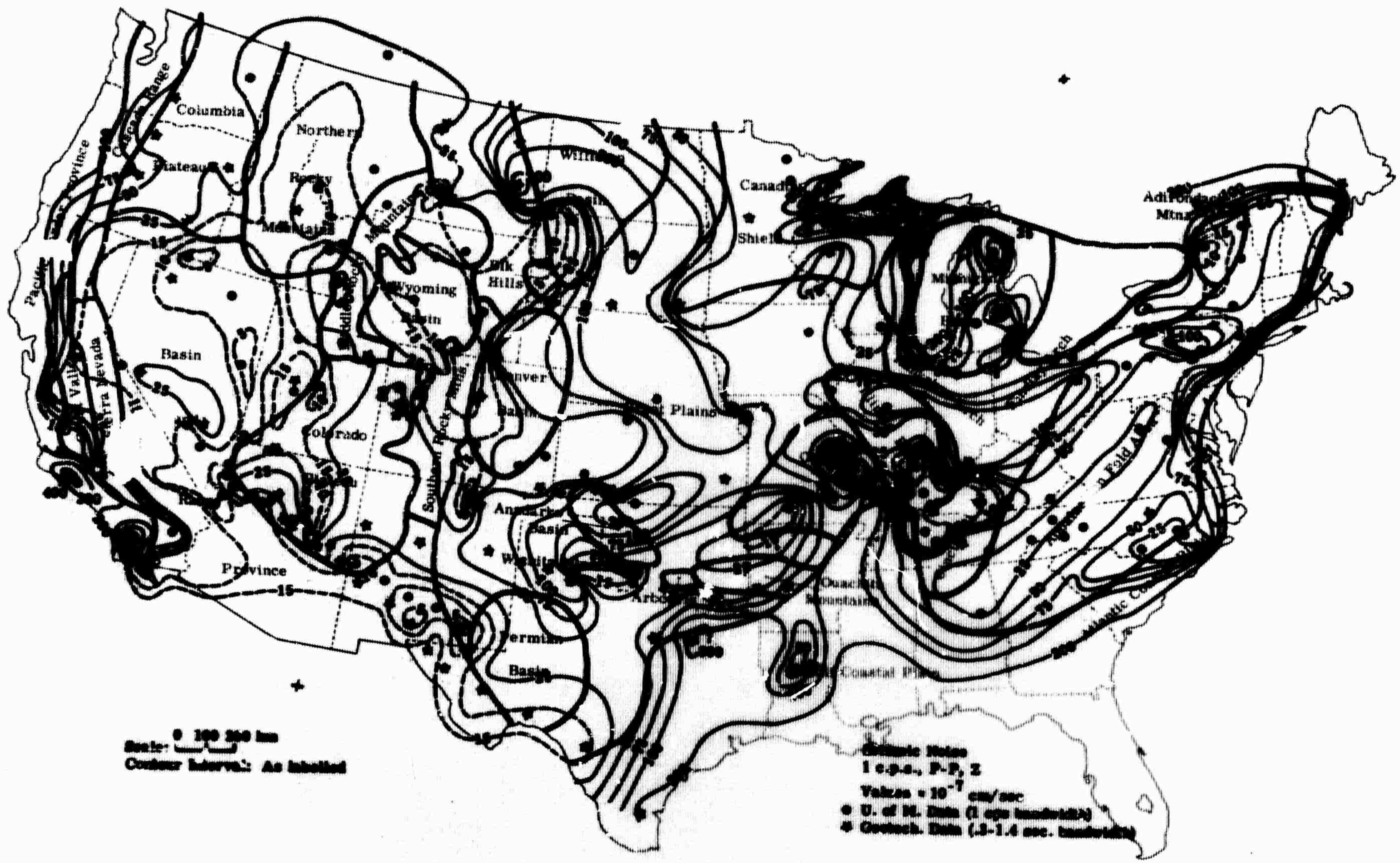


FIGURE 7a. ISO-PARTICLE-VELOCITY CONTOUR MAP OF THE CONTINENTAL UNITED STATES
FIGURE 7b. MAJOR TECTONIC PROVINCES OF THE CONTINENTAL UNITED STATES

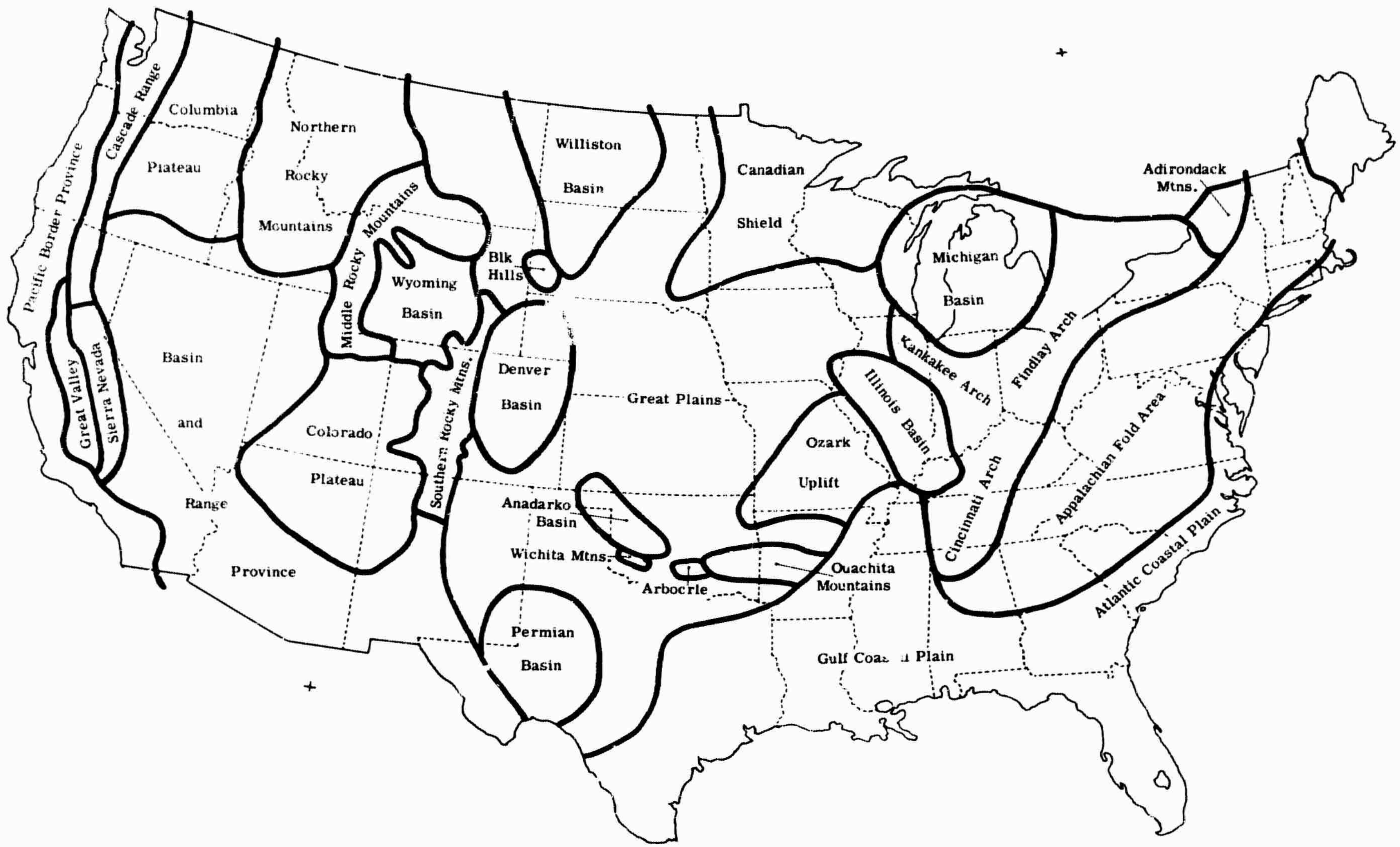


FIGURE 7b. MAJOR TECTONIC PROVINCES OF THE CONTINENTAL UNITED STATES

Recall from Fig. 4 that the value of the median for the ensemble averages at 1 cps (Z component) is approximately $18(10^{-7})$ cm/sec. In Fig. 7 we indicate by dash lines those iso-particle-velocity contours lower in value than $18(10^{-7})$ and by solid lines those higher in value than $18(10^{-7})$. On inspection one can judge the extent of specific noise levels in various regions by comparing the relative areas enclosed by the different contours. The maximum variation in noise level between physiographic environments is noted to be (a) greater than the maximum variation attributed to seasonal changes, as found by Romney [6] and (b) greater than the maximum variation attributed to meteorological causes, as investigated by the United ElectroDynamics Corporation [7].

Finally, it can be pointed out that particle-velocity contouring near oceanic boundaries indicates the width of the transitional zone from high ambient noise level at the coast to average ambient noise level inland. Figure 7 suggests this distance to be about 150 km along the west coast and, generally, a substantially greater distance along the east coast, both referring to the spectral amplitude at 1 cps.

## 2.5. CUMULATIVE DISTRIBUTIONS OF NOISE

The two-dimensional contour map shown in Fig. 7 indicates that there is substantial variation in 1 cps ambient noise as a function of location. In fact, inspection of the example noise spectra for short seismic periods, Fig. 13-22, suggests that the noise variation over the continental plane for a wide range of frequencies is considerable. Whereas the general form of the spectrum at and below 1 cps is rather constant, there are marked changes in the spectral shapes at frequencies above 1 cps.

We used the entire set of background measurements to form the ensemble averages, based on a collection of all space averages, and determined the distribution functions at discrete frequencies shown in Fig. 8 for the vertical component of ground-particle velocity. Mean amplitudes show a log-normal distribution with standard deviation $\sigma$ = 4 1/2 to 6 db, the greater deviations associated with higher frequencies.

The time stability of seismic noise is examined for sites where measurements of mean amplitude are available over varying time intervals. Two examples of these results are shown in Fig. 9 and 10, based respectively on multiple observations from small arrays at Shepherd, Montana, and Copper Harbor, Michigan. In Fig. 9 and 10 distributions of vertical amplitudes are examined for discrete frequencies over different time periods. The maximum frequency

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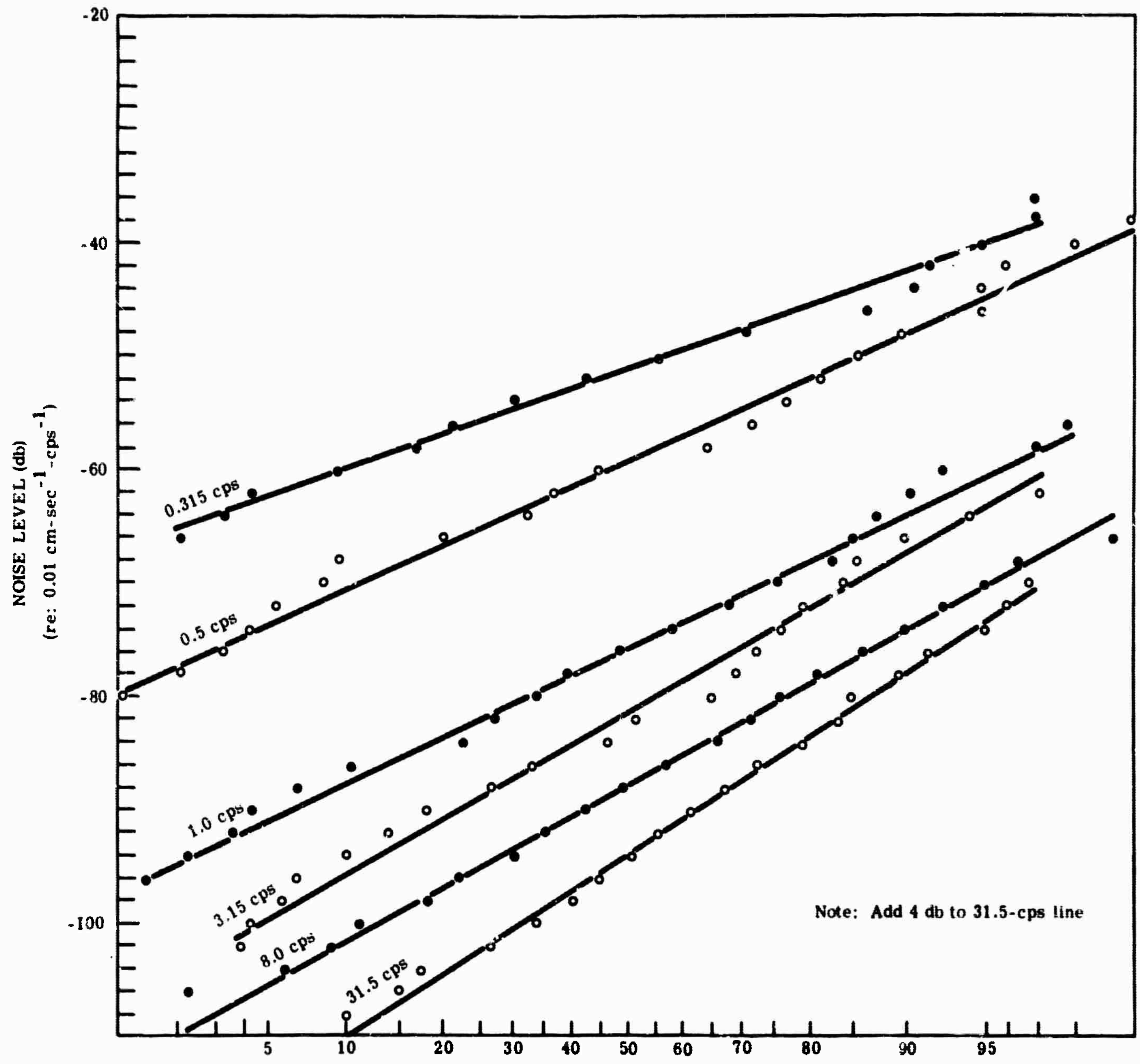


FIGURE 8. PROBABILITY DISTRIBUTIONS FOR ENSEMBLE AVERAGES (Z)

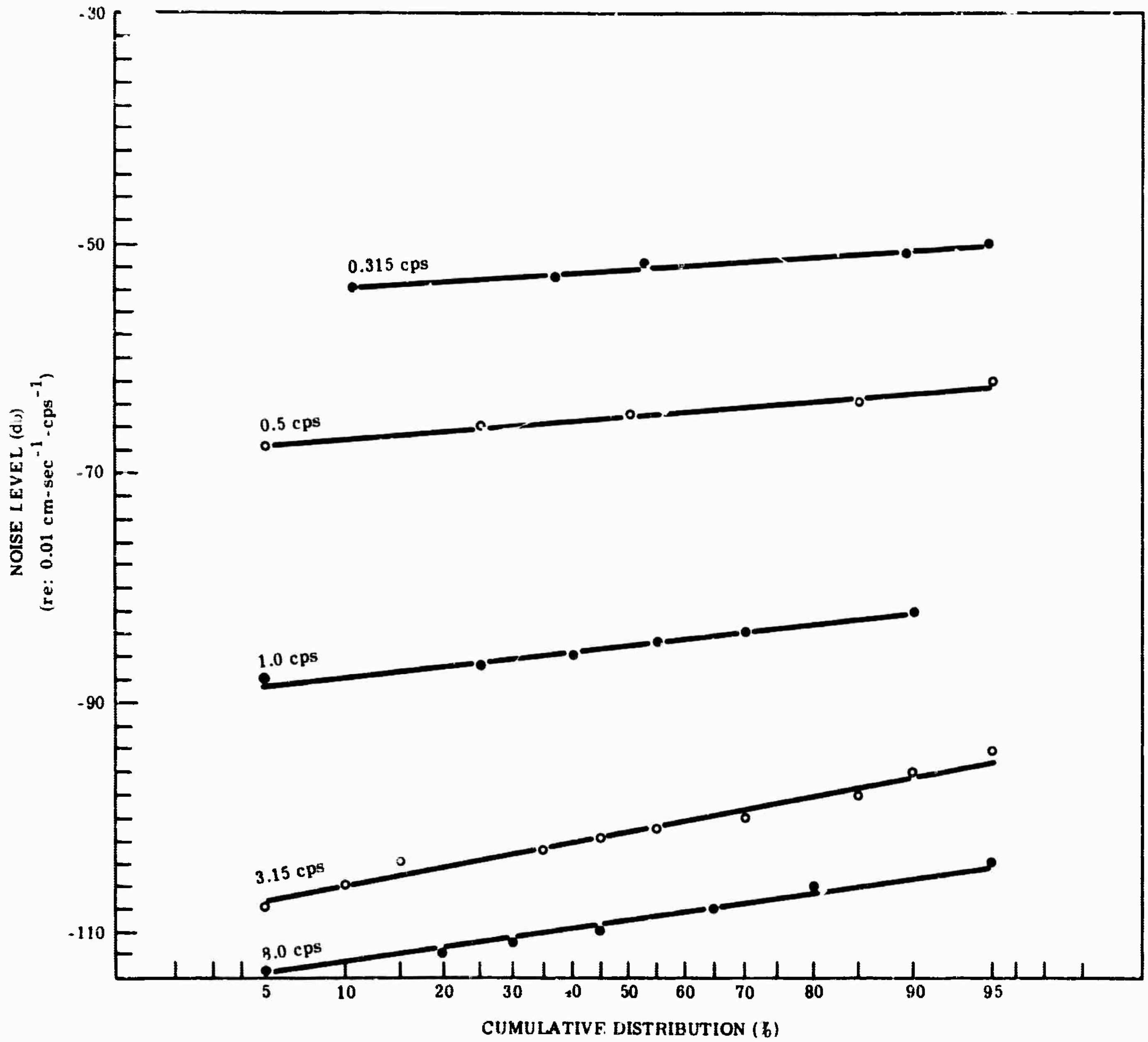


FIGURE 9. PROBABILITY DISTRIBUTIONS FOR SHEPHERD ARRAY (Z)

considered is that associated with the wavelength of the order of the maximum array dimension (correlation length). In all cases the noise amplitudes show a log-normal distribution. This distribution is in agreement with results obtained by Texas Instruments Incorporated, [8] who examined data published by Brune and Oliver [9] and reported the time variation of peak amplitude to be log-normal at three different locations.

From the time stability data and from the ensemble probability distributions, in which time is not necessarily fixed, it is desirable to infer something about the space distribution at fixed time. To do so, it is necessary to comment on (a) the statistical homogeneity of the seismic process, and (b) the adequacy of the process sampling.

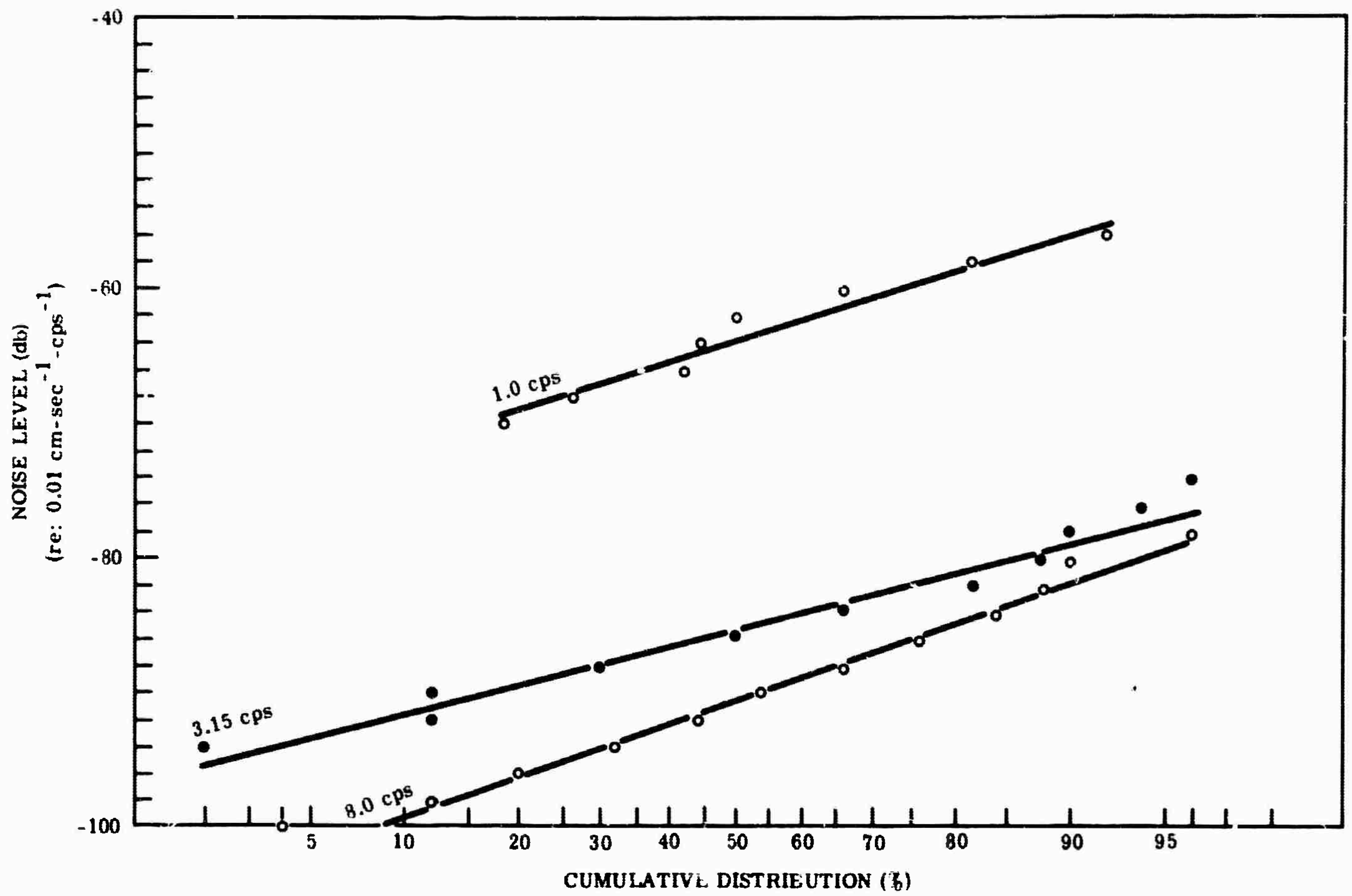


FIGURE 10. PROBABILITY DISTRIBUTIONS FOR COPPER HARBOR ARRAY (Z)

With respect to (a), we constructed means of the space samples in the eastern and western halves of the continental United States, using the 96-degree meridian as dividing line. Results are shown in Fig. 11. The spectral shapes are very similar. The difference in noise levels is about 8 db at high frequencies; it decreases with decreasing frequency. On the basis that the east and west averages do not differ greatly, we are tempted to assume that the seismic noise is sufficiently homogeneous.

With respect to (b), we can state that the distribution function is constructed over the continental plane, a region of linear dimension certainly more than ten times the correlation length. The latter is determined by the wavelength of the lowest-frequency noise considered in the analysis. Also the field recording equipment is broadband and the recorded noise is broadband, which reduces the length of time needed to get a reliable estimate of the distribution. For these reasons, we perhaps can assume that the space and time measurements constitute a representative sample.

The equivalence of space averages and time averages is supported by results (a) and (b) above, and by the time stability data. Thus we infer that the probability distribution of space averages for fixed time and widely-spaced stations is gaussian.

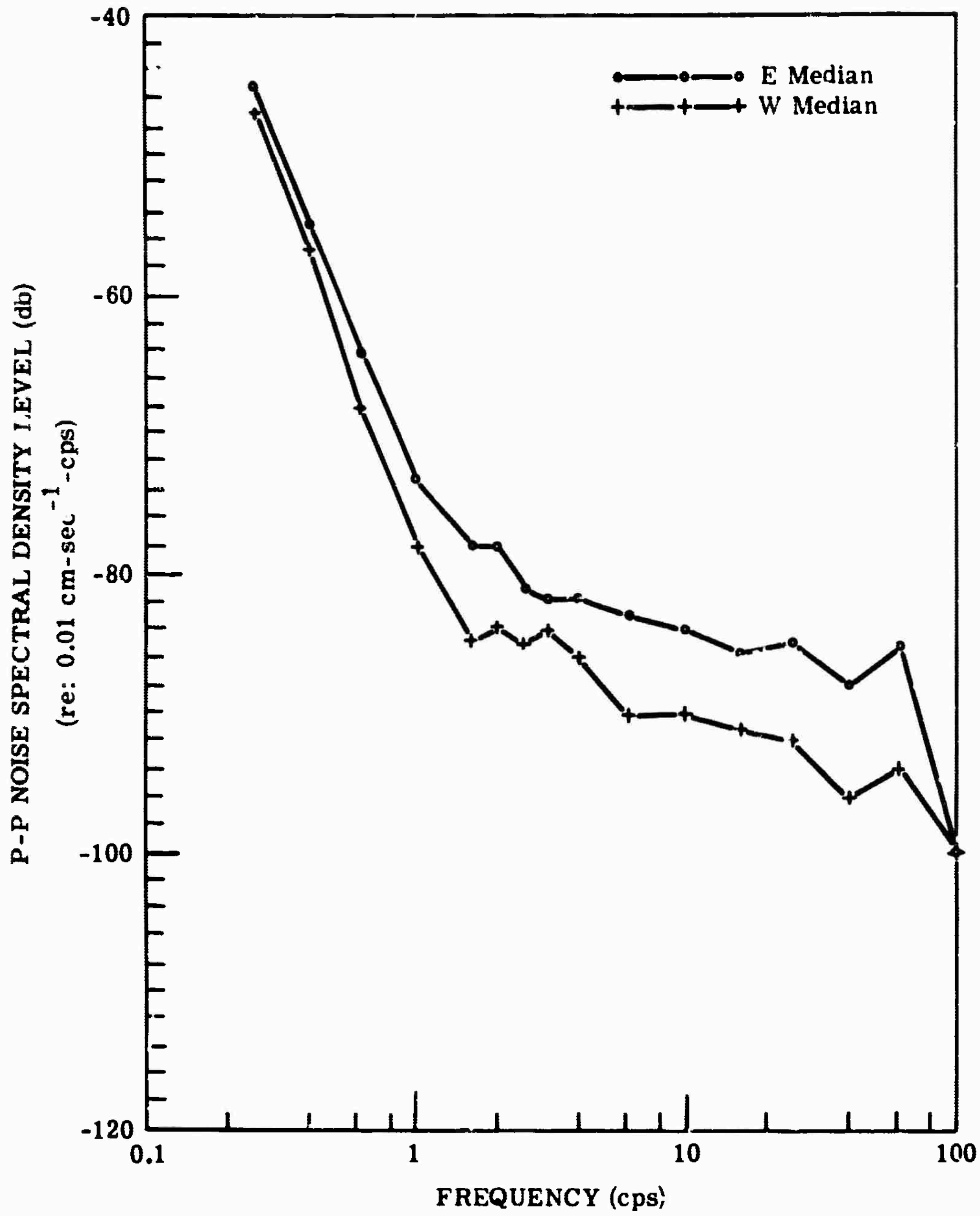


FIGURE 11. COMPARISON OF EAST AND WEST MEDIANS

## 2.6. RELATIVE COMPONENT AMPLITUDES

With the availability of three-component data for widely-spaced stations, it is possible to observe the ratio of horizontal and vertical amplitudes (H/Z) as a function of physiographic provinces. The theoretical value of H/Z for surface displacements of simple Rayleigh waves is about 0.68. In layered media (for example, a single layer overlying a half space of contrasting elastic properties), at large values of normalized wavelength (wavelength divided by layer thickness) the values of H/Z are different from and asymptotic to 0.68; at small values of normalized wavelength, H/Z increases.

Considering, then, that a significant part of short-period seismic noise consists of propagating Rayleigh waves, we anticipate a variation of H/Z with physiographic variation. The mean H/Z ratio was determined by averaging all stations within each of seven regional environments. Results are shown in Fig. 12. It is noted that at frequencies above about 2.5 cps, curves for different regions are interrelated and suggest no consistent contrast. Below 2.5 cps there is a separation of curves into two groups. The upper group contains mean curves for the lower Michigan Basin, central and southern interior plains, and upper Mississippi embayment regions. The lower group is associated with the Appalachian Mountains, northern Rockies, southwestern Lake Superior Shield area (Pre-Cambrian exposures) and the range areas of the Basin and Range Province. Thus below 2.5 cps regions characterized by sediments and distinct layered structure indeed do show higher values of H/Z than regions characterized by surface formations of massive basement rock-complexes.

A maximum difference in the average H/Z for various regions, as shown in Fig. 12, occurs between 1.5 and 2 cps. In fact, the magnitude of the effect near 2 cps relative to higher and lower frequencies suggests that the earth's crust has an anomalous filtering effect on this part of the seismic spectrum. This frequency effect on the transmission of surface waves may partially explain the peak in the noise spectrum at 2 cps.

The curve identifying the lowest H/Z values is for stations in the southeastern Basin and Range Province. The very quiet stations of this group often show H/Z values lower than the theoretical value for simple Rayleigh waves. This observation could support the suggestion that P-wave energy arriving at small angles of incidence is contributing significantly to the total seismic-noise spectrum at low background sites.

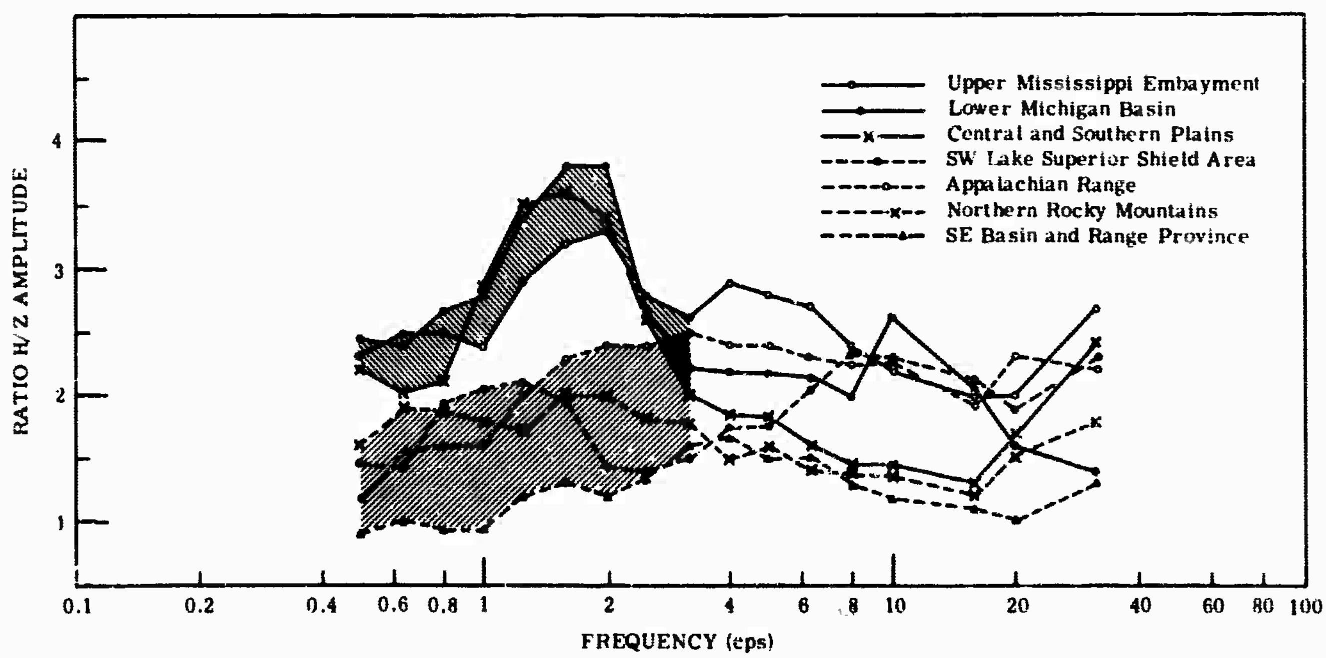


FIGURE 12. H/Z RATIO FOR SEVEN PHYSIOGRAPHIC PROVINCES OF UNITED STATES

## 3
## CONCLUSIONS

Measurements of spectral density levels of short-period seismic noise are obtained for points distributed throughout the continental United States and at a few non-North American locations. Noise amplitudes and gradients in the far field correlate, on a regional basis, with major physiographic provinces, as revealed by iso-particle-velocity contouring.

The ensemble of space and time samples of noise are examined to illustrate the "average" spectrum and dispersion for three orthogonal components of ground-particle velocity in the range 0.25 to 100 cps. The general level of noise spectral density varies with geography across the entire spectrum. The general shape of the noise-spectral density holds up at frequencies near and below 1 cps but fluctuates with geography at frequencies above 1 cps.

Probability distributions of noise amplitudes based on a collection of space averages and time averages are presented for several frequencies. Measured time averages are found to be log-normal. Space averages for fixed time and widely-spaced stations are suggested to be gaussian, based partly on evidence supporting the equivalence of space averages and time averages.

The mean ratio of horizontal-to-vertical noise amplitude (H/Z) is determined for multiple stations in seven broad physiographic regions. The observed H/Z generally exceeds the theoretical value for simple Rayleigh waves and shows a frequency-dependent variation with location. Areas characterized by sediments and distinct layered structure show high values of H/Z, particularly in the range 1.5 to 2 cps, relative to areas where massive basement rock-complexes exist at the crustal surface. H/Z values observed for very quiet sites in southwestern United States suggest that P-wave energy impinging on surface stations at small angles of incidence may be contributing substantially to the noise spectrum at low-background sites.

## 4
## FISCAL DATA

The total fiscal expenditure for this study was $65,421. This included the following capital equipment acquisitions:

| | |
|---|---|
| Applied Dynamics Analog Computer Components | $2400 |
| HS-10 Seismometers and Accessories | 975 |
| XY Recorder and Accessories | 980 |
| Total | $4355 |

## Appendix

## THREE-COMPONENT SPECTRA

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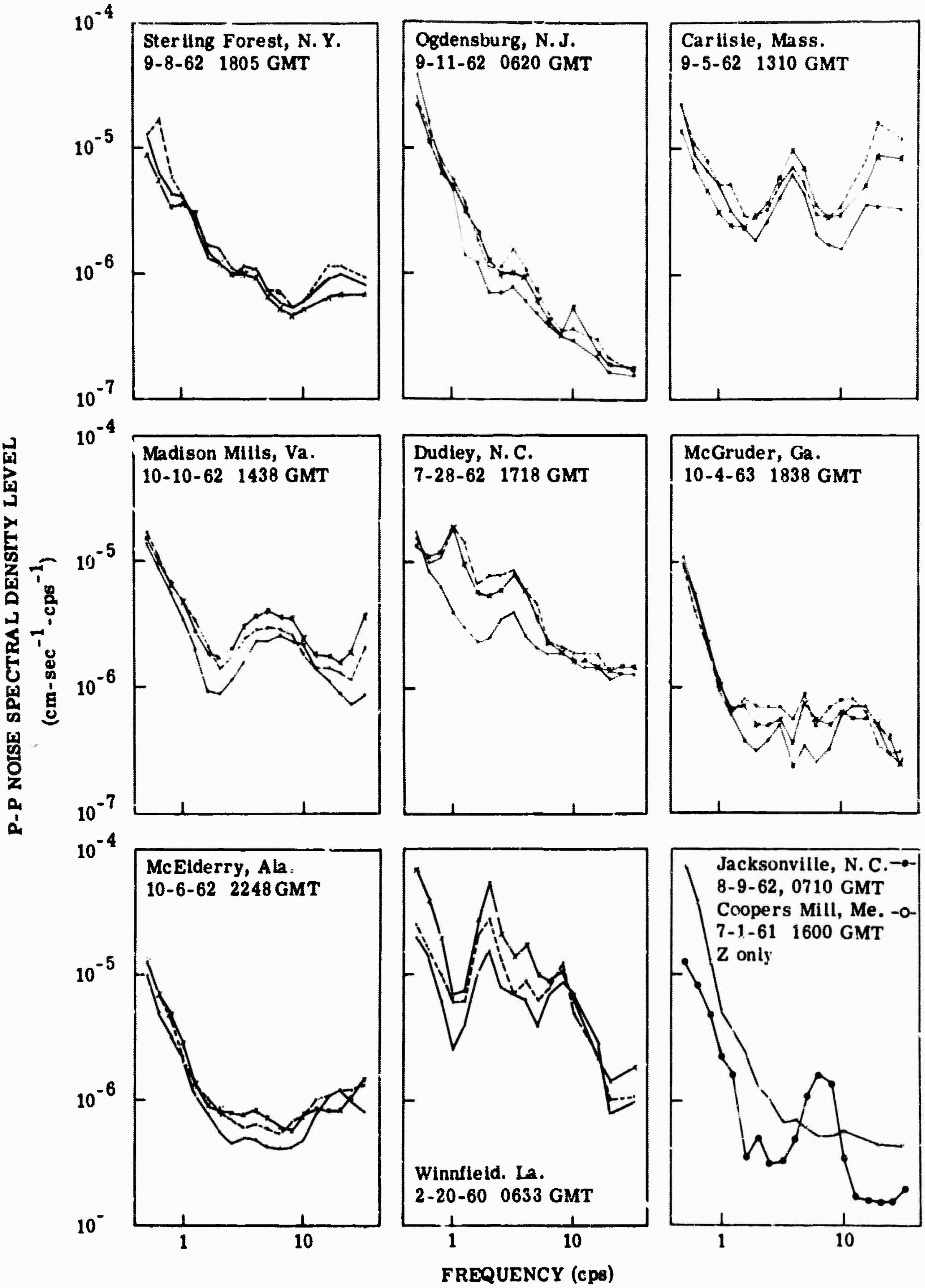


FIGURE 13. THREE-COMPONENT SPECTRA FOR EAST AND SOUTHEAST COASTAL STATIONS.

—x— = N-S; --•-- = E-W; —•— = Z.

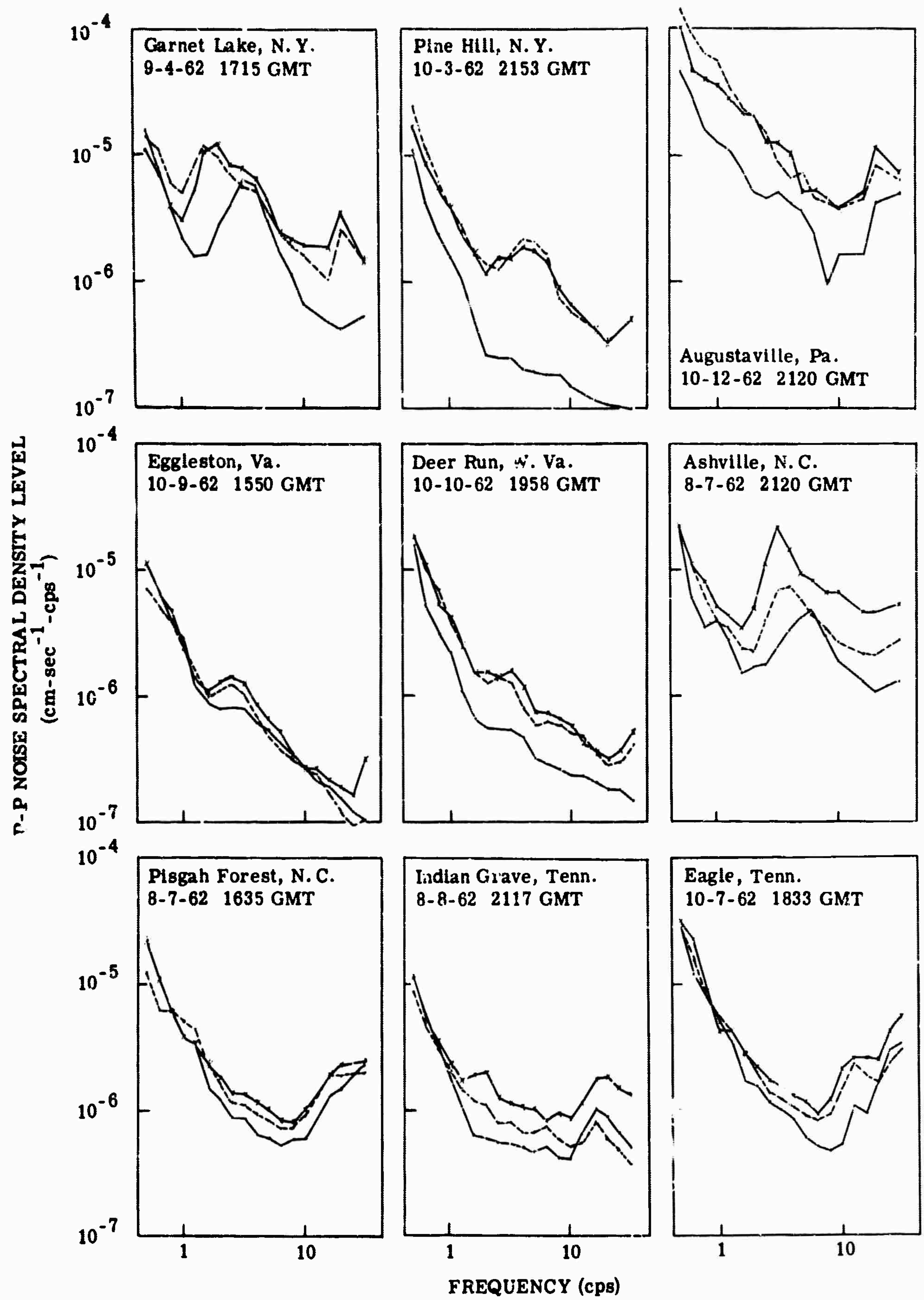


FIGURE 14. THREE-COMPONENT SPECTRA FOR APPALACHIAN STATIONS.

—x— = N-S; --•-- = E-W; —•— = Z.

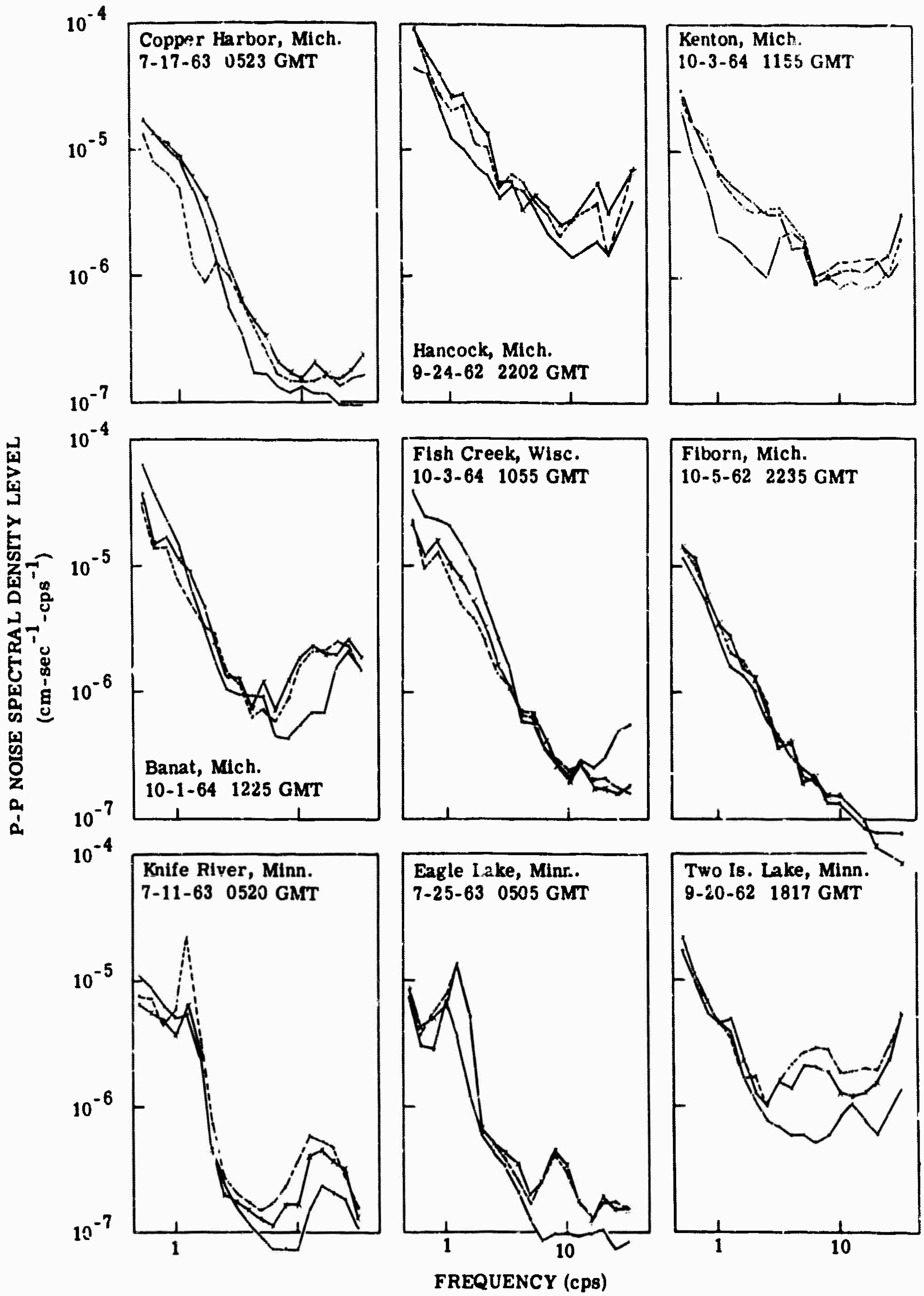


FIGURE 15 THREE-COMPONENT SPECTRA FOR S.W. LAKE SUPERIOR DISTRICT.

—x— = N-S; --•-- = E-W; —•— = Z.

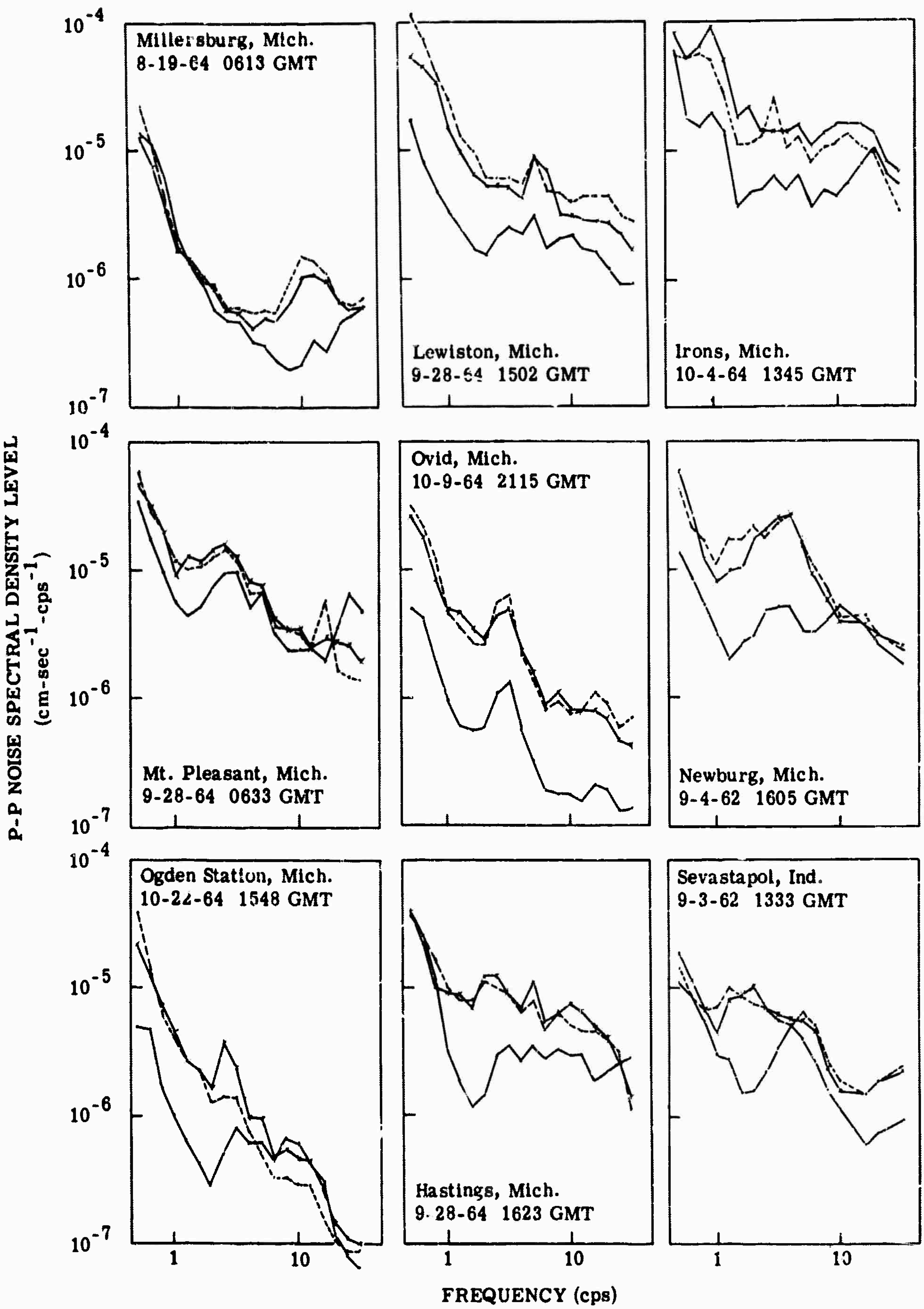


FIGURE 16. THREE-COMPONENT SPECTRA FOR LOWER MICHIGAN BASIN.

—x— = N-S; --•-- = E-W; —•— = Z.

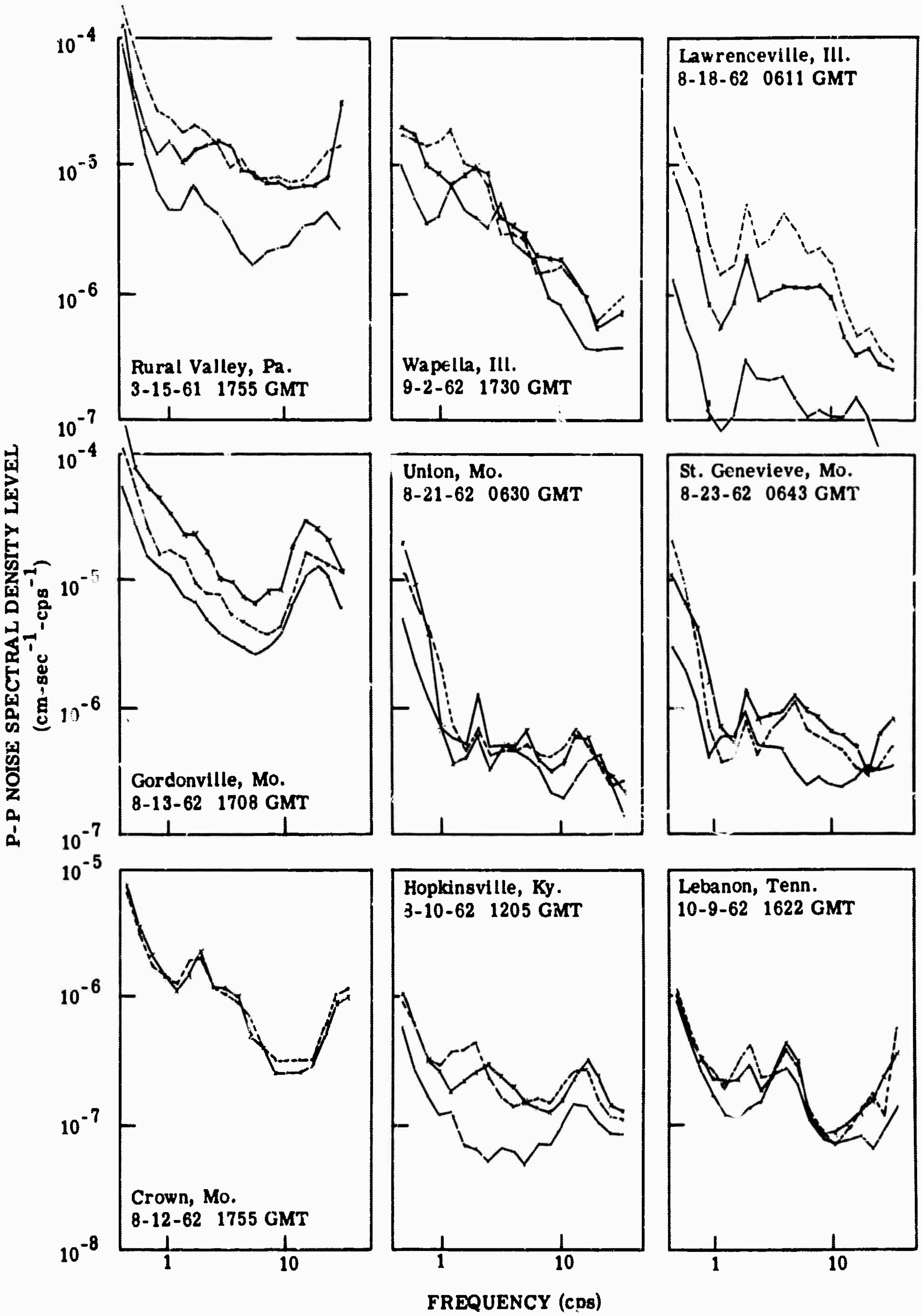


FIGURE 17. THREE-COMPONENT SPECTRA FOR APPALACHIAN BASIN AND UPPER MISSISSIPPI EMBAYMENT.

—x— = N-S· --•-- = E-W: —•— = Z.

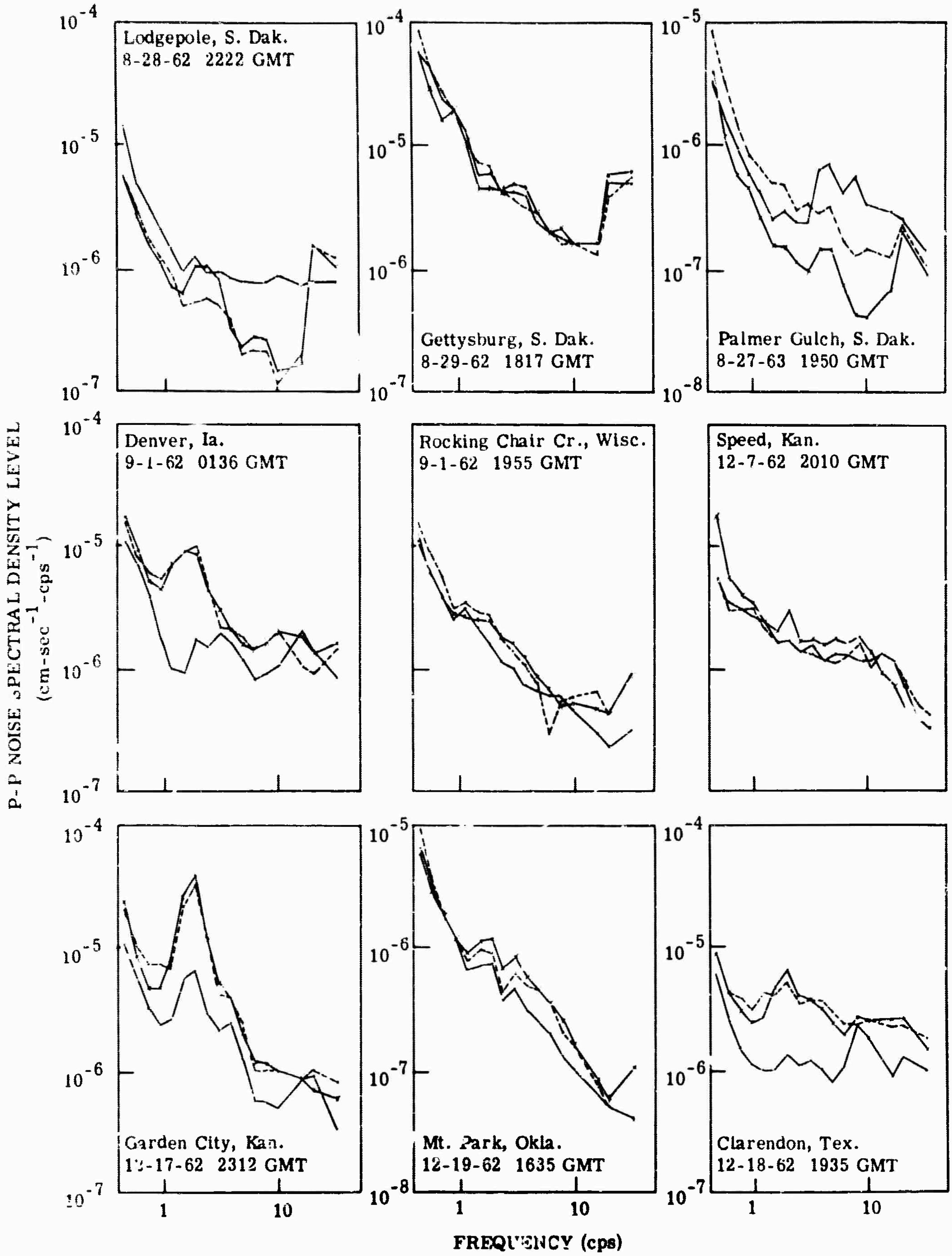


FIGURE 18. THREE-COMPONENT SPECTRA FOR CENTRAL AND SOUTHERN INTERIOR PLAINS.

—x— = N-S; —•— = E-W; —•— = Z.

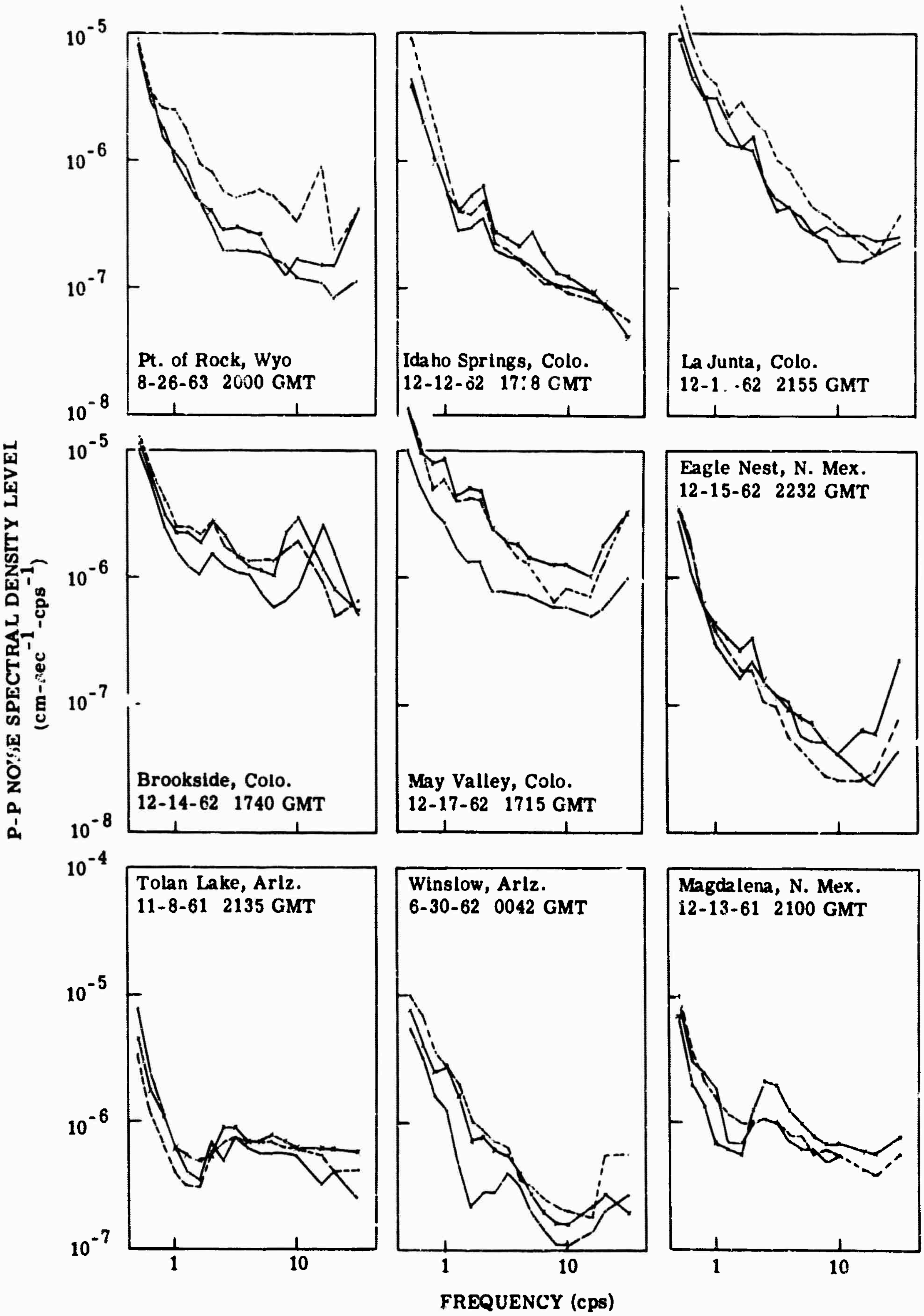


FIGURE 19. THREE-COMPONENT SPECTRA FOR CENTRAL AND SOUTHERN ROCKIES AND VICINITY.

—x— = N-S; --•-- = E-W; —•— = Z.

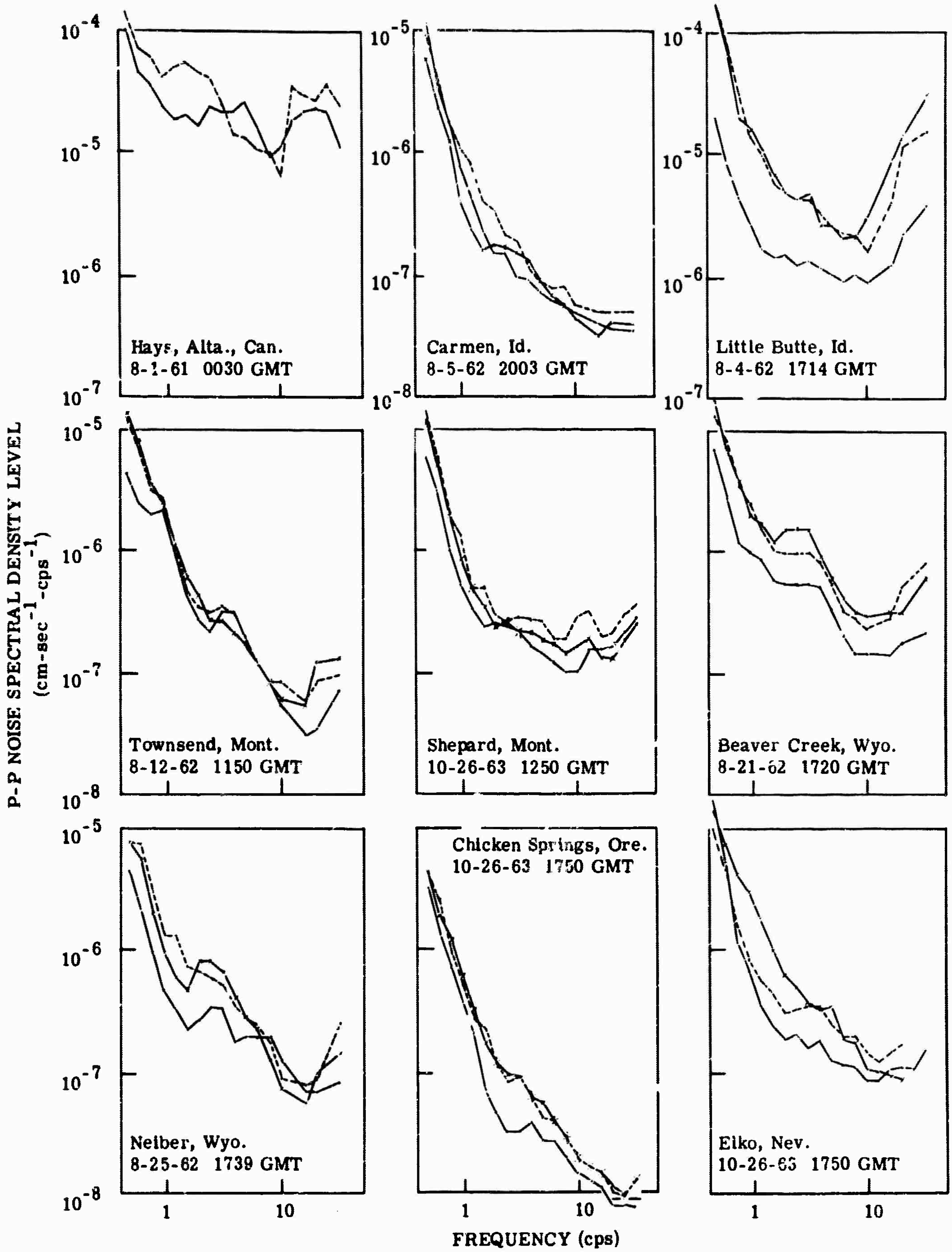


FIGURE 20. THREE-COMPONENT SPECTRA FOR NORTHERN ROCKIES AND VICINITY.

—x— = N-S; --•-- = E-W; —•— = Z.

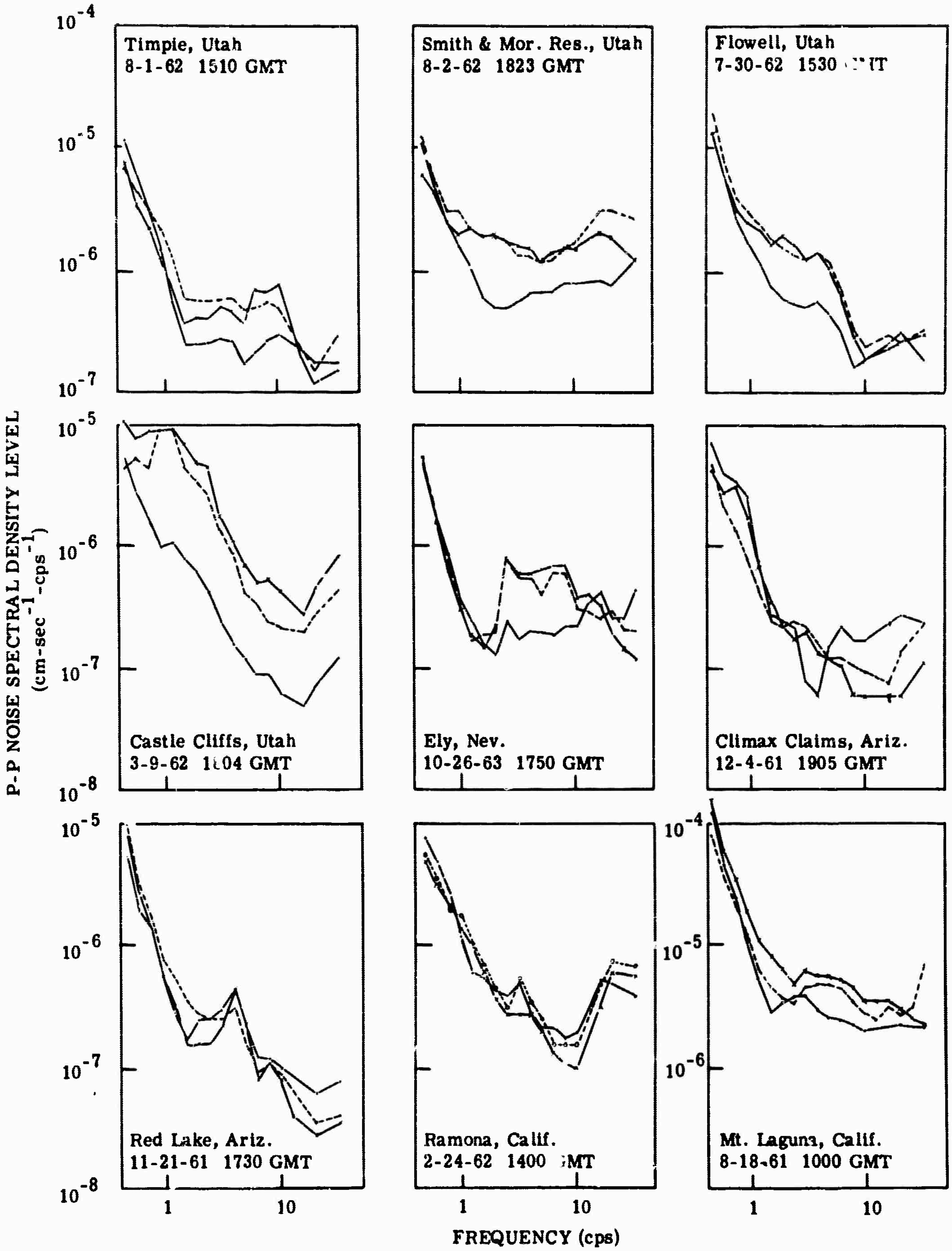


FIGURE 21. THREE-COMPONENT SPECTRA FOR BASIN AND RANGE PROVINCES AND VICINITY.

—x— = N-S; --•-- = E-W; —•— = Z.

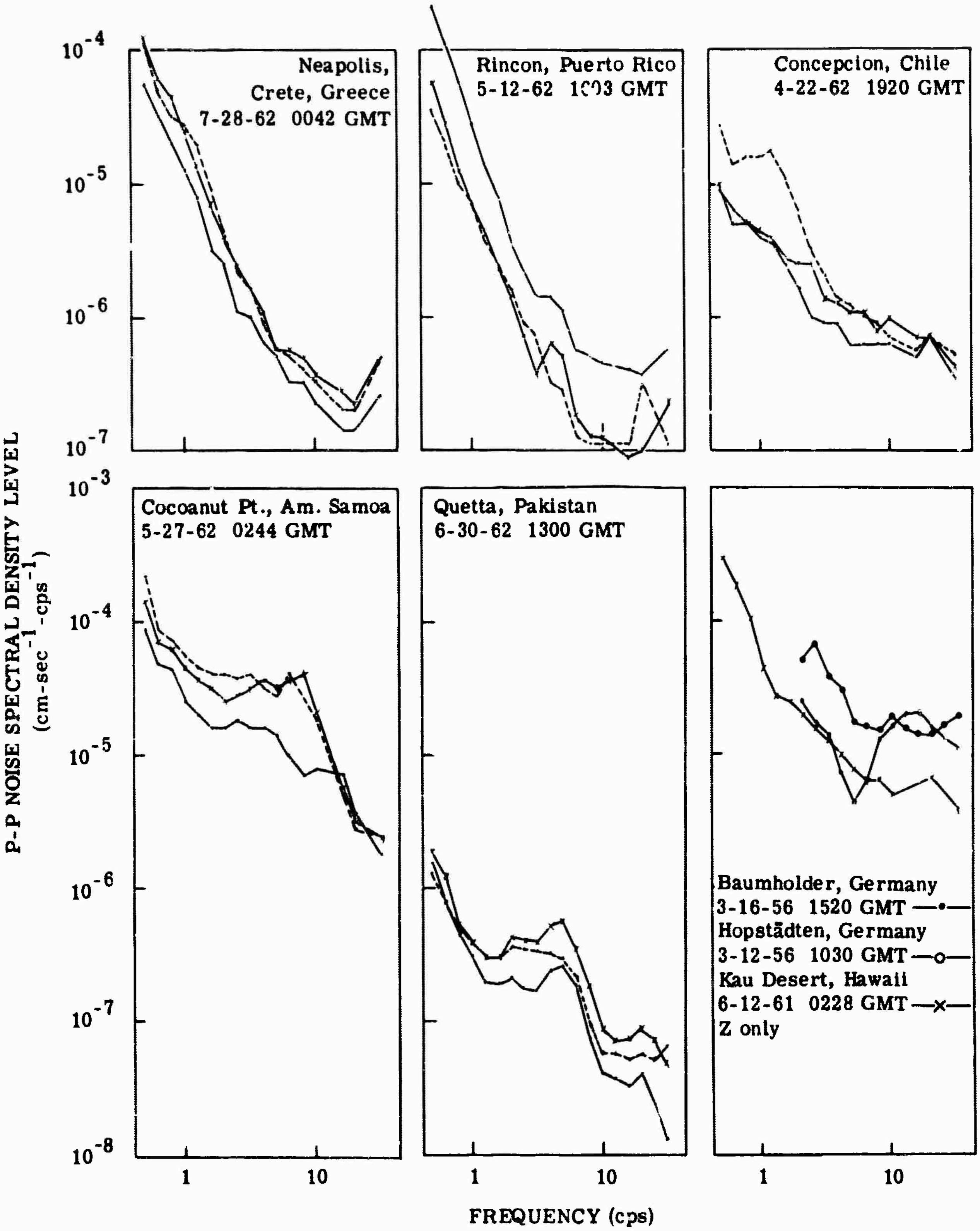


FIGURE 22. THREE-COMPONENT SPECTRA FOR NON-NORTH AMERICAN SITES.

—×— = N-S; --•-- = E-W; —•— = Z.

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