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LARGE-ARRAY SIGNAL AND NOISE ANALYSIS

Special Scientific Report No. 19

NOISE SUPPRESSION BY LONG-PERIOD INFINITE-VELOCITY PROCESSORS

Frank H. Binder, Program Manager
Telephone: 1-214-238-3473

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

Contract No. AF 33(657)-16678

Prepared for
AIR FORCE TECHNICAL APPLICATIONS CENTER
Washington, D.C. 20333

Sponsored by
ADVANCED RESEARCH PROJECTS AGENCY
ARPA Order No. 599
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attn: VSC, Wash. D.C. 20333

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TABLE

ILLUSTRATIONS

ILLUSTRATIONS (CONTD)

SECTION I

INTRODUCTION

This report presents the results of various infinite-velocity processing schemes applied to two long-period noise samples recorded at the Montana LASA on 2 and 3 December 1966. The schemes are applicable to the extraction of high-velocity P phases in the presence of ambient noise. The methods employed are

- Straight summation
- Multichannel signal extraction with an infinite-velocity signal model
- Multichannel prediction filtering

Various combinations of sensors were used in the application of the first two methods. Each method was applied to both samples.

The two 70-min noise samples chosen are generally representative of the winter-season long-period noise samples studied to date, although certain individual features are evident. Recording times of the two samples were separated by about 6 hr, thus allowing an estimate of the effects of the noise field's short-term time stability.

The main purposes of the work were

- To evaluate each processing scheme using various array configurations
- To evaluate the relative performance of the processing schemes using identical sensor arrays
- To determine the relative performance of multichannel filters when designed from one noise sample and applied to each of the samples

SECTION II

PROCEDURES

For purposes of comparison, Table II-1 lists the processing schemes applied.*

Prior to processing, the data were resampled to a 2-sec sampling interval. Noise statistics for the filter design were developed from the 3 December noise sample prewhitened by a 7-point deconvolution filter.

The processor output power density spectra were obtained by Fourier-transforming the output autocorrelation function with a Bartlett window. The output correlation functions contained 50 lags in all cases except for the two multichannel signal-extraction cases having 19 filter points, which contained 19 lags. Power spectral density amplitudes were expressed in db relative to an arbitrary level.

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*For the reader's convenience, Table II-1 appears as a foldout at the end of this report.

SECTION III

PRESENTATION OF RESULTS

A. METHODS OF PRESENTATION

To compare the application of different processors to the same noise sample, power-density spectra of the processor outputs are presented. To compare the performance of one processor when applied to the two samples, results are presented as noise power reduction relative to A0 vertical. To avoid ambiguity, no direct comparison is made between processors for which different spectral windows have been used.

B. PERTINENT CHARACTERISTICS OF THE NOISE SAMPLES

Special Scientific Report No. 12 presented the salient features of the 2 and 3 December noise samples.* For clarity and continuity of exposition, some of that discussion will be repeated in this report.

Figure III-1 shows the power-density spectra of the 2 and 3 December samples. These are similar in general shape, characterized by dominant peaks near 0.065 Hz and 0.135 Hz, and have a relative null near 0.11 Hz. They differ principally in that the 2 December spectrum falls off less rapidly above 0.15 Hz and possesses a more pronounced peak near 0.2 Hz. These spectra were obtained using a 50-lag window.

Figures III-2 and III-3, reproduced from Special Scientific Report No. 12, show wavenumber spectra from the vertical arrays at 0.06 Hz for the 2 and 3 December samples. Both spectra are dominated

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*Texas Instruments Incorporated, 1967: Analysis of Long-Period Noise Large-Array Signal and Noise Analysis, Spec. Scientific Rpt. No. 12, Contract AF 33(657)-16678, 18 Oct.

by a source located in a northeasterly direction with a velocity of approximately 3.5 km/sec. It has been postulated in Special Scientific Report No. 17 that this noise is storm-generated.* Of particular interest is the fact that the predominant noise is of relatively low velocity and originates from a point-like source.

The wavenumber spectra of the horizontal arrays and the vertical array at other frequencies, though not shown here, have been found to exhibit features similar to those shown.**

C. VARIATION IN SUMMATION PROCESSOR PERFORMANCE WITH ARRAY CONFIGURATION

Figure III-4 shows the power-density spectra of the outputs of three summation processors applied to the 2 December sample. Processors used were the 9-, 12-, and 18-channel straight summation described in Table II-1.

When the spectra are compared, significant features are found.

- The 12-channel summation processor is superior in the vicinity of the 0.065-Hz peak
- The 9-channel summation processor is superior in the region between 0.07 Hz and 0.09 Hz
- The 18-channel summation processor is clearly superior above 0.13 Hz

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*Texas Instruments Incorporated, 1967: Correlation between Storms at Sea and LASA Long-Period Noise, Large-Array Signal and Noise Analysis, Spec. Scientific Rpt. No. 17, Contract AF 33(657)-16678, 18 Dec.

**Large-Array Signal and Noise Analysis, Spec. Scientific Rpt. No. 12.

- The most pronounced differences occur in the vicinity of the 0.06-Hz and 0.14-Hz peaks; the 12-channel summation processor is superior at the former, and the 18-channel summation processor is superior at the latter. At other regions, performance of the summation processors differs by only 2 to 3 db, at most

- Perhaps the most significant feature of this comparison is that no summation processor is superior to the others over the entire frequency range

Shown in Figure III-5 are the output spectra of four summation processors applied to the 3 December sample. The processors are the 5-, 9-, 12, and 20-channel summation processors (Table II-1).

Comparison reveals the following.

- The 5-channel processor utilizing the A0 and B-ring verticals achieves a 2- to 3-db noise reduction near the 0.065-Hz peak and a 1- to 5-db reduction elsewhere
- Performances of the 9-, 12-, and 20-channel processors applied to the 3 December sample are similar to those of the 9-, 12, and 18-channel processors applied to the 2 December sample

D. VARIATIONS IN MCF PERFORMANCE WITH ARRAY CONFIGURATION

The noise reduction achievable by MCF infinite-velocity signal extraction is dependent on number of seismometers, array size, and choice of seismometer, i.e., vertical or horizontal.

Output spectra of three signal-extraction filters, utilizing only vertical seismometers, are shown in Figure III-6. The 5-channel signal-extraction filter uses the A0 and B rings; the 9-channel filter uses the A0, C, and D rings; and the 12-channel filter uses the A0, C, D, and E rings. For exact configurations, again refer to Table II-1 (for 31 filter points).

The 9-channel filter gives a 4- to 6-db improvement over the 5-channel filter above 0.05 Hz. Adding the E ring (12-channel) yields another 1- to 2-db improvement in this range, except in the vicinity of the 0.06-Hz peak where performance is slightly degraded.

The 12-channel MCF shows its greatest comparative noise reduction over the 9-channel MCF below 0.05 Hz; in this same range, the 9-channel MCF shows its least comparative reduction over the 5-channel MCF. However, above 0.05 Hz, the 9- and 12-channel processors are essentially equivalent.

Some insight into the effectiveness of the horizontals in reducing noise can be gained by examining Figures III-7 through III-9.

In Figure III-7, the 12-channel MCF is compared to a 14-channel MCF utilizing the A0 and B-ring verticals and horizontals, less B2 north (Table II-1, 31 filter points). The 12-channel processor shows a slight advantage, except in the vicinity of the dominant peaks and particularly in the 0.06-Hz peak where the 14-channel processor gives 1 to 2 db more noise reduction.

Figure III-8 compares the 5- and 14-channel processors. Here, the superiority of the 14-channel processor is directly attributable to the addition of horizontals and amounts to as much as 8 to 9 db on the slope of the dominant peak and generally 2 to 6 db elsewhere.

A similar comparison is given in Figure III-9. Shown are the output spectra of a 4-channel and a 13-channel MCF processor, each applied to the 3 December sample and each having 19-point filters. The 4-channel elements are A0, B2, B3, and B4 verticals; the 12-channel elements are those plus A0, B1, B3, and B4 horizontals. As in the previous examples, the superiority of the 12-channel processor is due entirely to the inclusion of the horizontal elements. Certain parameters in the design of these filters were changed slightly from the previous cases and, in addition, the power spectra were obtained using a shorter-lag window; therefore, it is not possible to evaluate directly the effect of reduced filter length.

E. STRAIGHT SUMMATION VS MULTICHANNEL SIGNAL EXTRACTION

Straight summation and MCF signal-extraction processors are compared in Figures III-10 through III-13.

Shown in Figure III-10 are the power-density spectra of the 5-channel MCF and 5-channel summation processors, each using the A0 and B-ring vertical seismometers for the 3 December sample. The MCF processor is greatly superior to the summation processor in the vicinity of the 0.065-Hz peak and moderately superior at higher frequencies. The superiority amounts to approximately 14 db near the peak and generally 4 to 6 db at the higher frequencies.

In Figure III-11, the 9-channel summation processor is compared to the 9-channel signal-extraction MCF for the 3 December sample, utilizing the same seismometers. As in the previous case, the MCF output is the extraction of A0 vertical using 31 filter points. Above 0.02 Hz, the MCF processor is superior to straight summation by 2 to 6 db, with the greatest superiority in the vicinity of the 0.06-Hz peak.

Figure III-12 similarly compares the 12- and 20-channel straight summation and the 12-channel MCF processors. Again, the MCF is superior to either summation processor above 0.02 Hz, except for a small region near 0.14 Hz where the 20-channel straight summation is slightly better. In fact, only in this 0.14-Hz region do any of the summation processors significantly outperform the 9-channel MCF.

Shown in Figure III-13 are the power-density spectra of the - and 12-channel straight summations and the 9- and 12-channel MCF outputs for the 2 December sample. The filters were developed from 3 December statistics.

Although the MCF performances are down somewhat from those for the 3 December sample, they still compare favorably with summation performances and outperform the straight summations over a significant portion of the spectrum. Extrapolation from the performance of the 3 December noise sample suggests that the MCF performance was degraded on the order of 3 db (near the 0.065-Hz peak) when applied to the 2 December noise sample.

F. MULTICHANNEL PREDICTION-ERROR FILTER

Shown in Figure III-14 is the spectrum of error obtained in predicting A0 vertical from A0, B1, B3, and B4 horizontals with 19-point filters. The spectra of A0 vertical and the output of the 12-channel signal-extraction filter are also shown. The 8-channel prediction-error filter is considerably poorer than the signal-extraction filter; the difference amounts to approximately 10 db over the full frequency range.

The large difference between the vertical component that remains after predicting off that energy common to the horizontal sensors and the vertical component that remains after velocity filtering suggests that the vertical sensors might contain significant energy in other than the Rayleigh mode. Being conducted is an investigation of the vertical component noise after all horizontals have been used to predict off as much as possible of the vertical components.

G. VARIATIONS IN PERFORMANCE WITH DESIGN STATISTICS

As mentioned previously, certain multichannel filters developed from 3 December statistics were convolved with the 2 December sample. As is evident from Figures III-1 through III-3, the 2 December noise field differs from the 3 December noise field in two major respects: the dominant noise source is shifted slightly in K space and A0 vertical power is slightly concentrated at the higher frequencies. Since the 3 December data were whitened in frequency but not in K space prior to filter design, the shift in K space would be expected to contribute more to the degradation of filter performances when applied to the 2 December sample than would the slight concentration of power at higher frequencies. However, this cannot be verified from the results.

Noise-power reduction of the 2 December and 3 December samples, relative to the corresponding A0 vertical achieved using the 12-channel signal-extraction filter, is shown in Figure III-15. Figures III-16 and III-17 are similar plots for the 9-channel signal-extraction and the 8-channel prediction-error filters, respectively. In all cases, the most significant differences occur at the higher frequencies. In the vicinity of the 0.065-Hz peak, the differences are generally less than 2 db.

Output spectra of the 4- and 12-channel 19-point filters for the two samples are compared in Figure III-18. Since these were obtained using a shorter-lag window, the A0 vertical power spectra are not shown in the same figure.

H. CONCLUSIONS

The following conclusions can be drawn from the comparison of the various processing schemes.

- For separating P-wave signals or surface modes widely separated from the noise (these should be essentially similar problems using vertical sensors), the 9-element array (A0, C, and D rings) using multichannel filtering is more effective than any straight summation and very nearly as effective as the 12-channel MCF (A0, C, D, and E rings).

- The vertical 5-channel MCF (A0 and B ring) is somewhat inferior to the 9-channel MCF (A0, C and D rings), but compares favorably with any of the summation processors.

- An MCF using the vertical channels in a signal-extraction mode and the horizontals in a prediction mode from A0 and the B ring suppresses the noise as effectively as the vertical 12-channel MCF using A0, C, D, and E rings. This type of processing would be applicable to the extraction of distant P waves.

- Use of only the horizontals in a prediction mode gives significantly poorer noise rejection than other forms of processing.

- Of the summation processors considered, the 5-channel (A0 and B ring) is definitely the least effective in reducing noise. Of the remaining summation processors, none possesses a clear-cut advantage over the full frequency range. When judged by total power reduction, the three summation processors (9-channel, 12-channel and 18- or 20-channel) appear approximately equivalent.

One should recall that these noise data were highly concentrated in K space. Conclusions about the effectiveness of various numbers of sensors and their configurations might not be valid for a more isotropically distributed noise field.

I. SUGGESTIONS FOR FURTHER STUDY

The excellent noise rejection obtained by the vertical-horizontal processor using A0 and B-ring elements suggests that the effectiveness of very small arrays be explored further. A small array using vertical and horizontal elements rotated to be orthogonal to a sought Rayleigh-mode signal might be a very effective surface-mode processor. If this proves to be the case, very small long-period arrays should be made considerably more attractive.

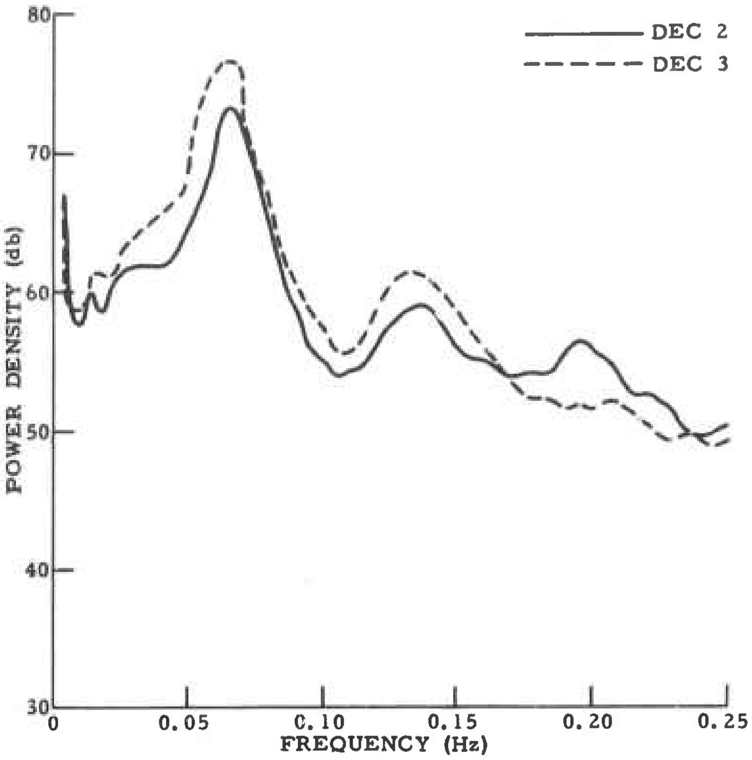

Figure III-1. Power-Density Spectra of A0 Vertical for 2 and 3 December Noise Samples

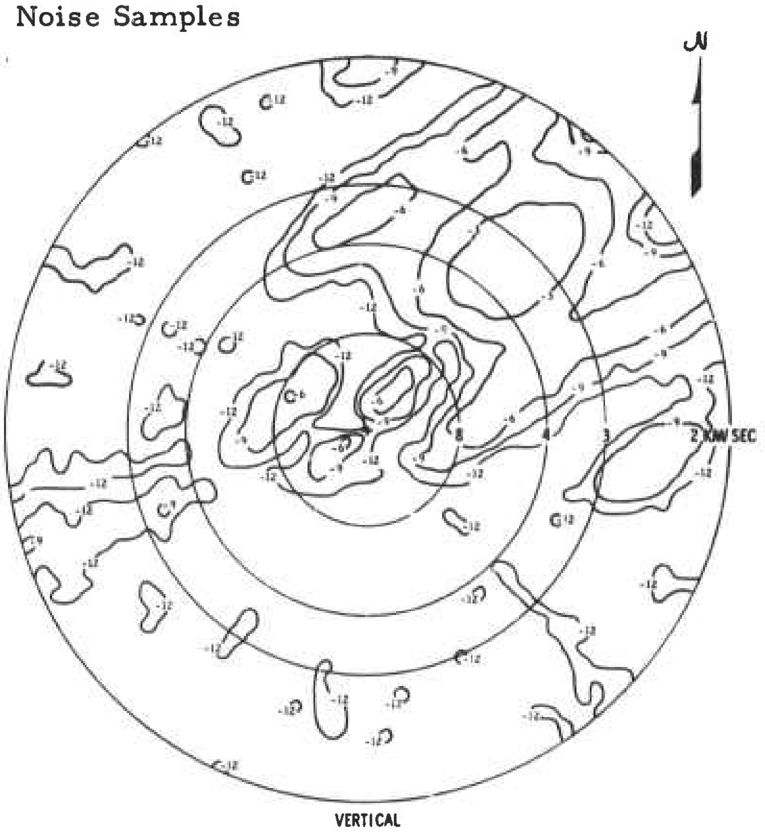

Figure III-2. Wavenumber Spectrum of Vertical Components at 0.06 Hz, 2 December Sample

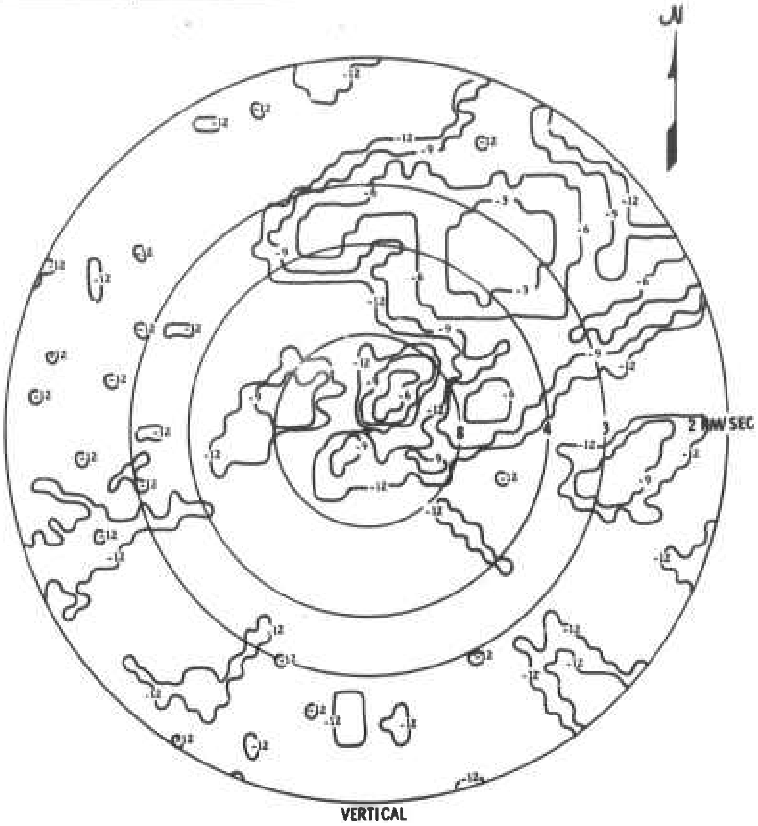

Figure III-3. Wavenumber Spectrum of Vertical Components at 0.06 Hz, 3 December Sample

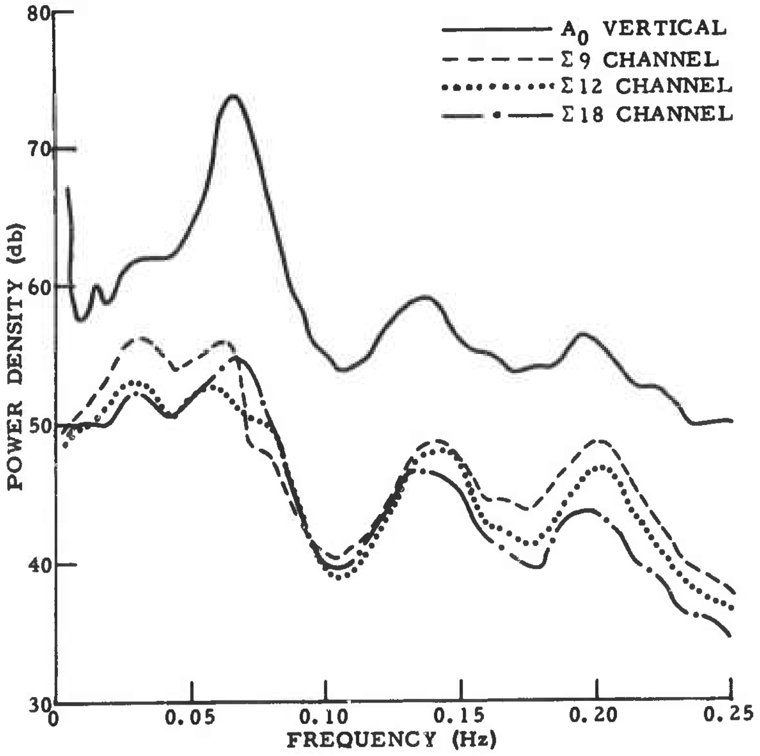

Figure III-4. Power-Density Spectra of Summation-Processor Outputs, 2 December

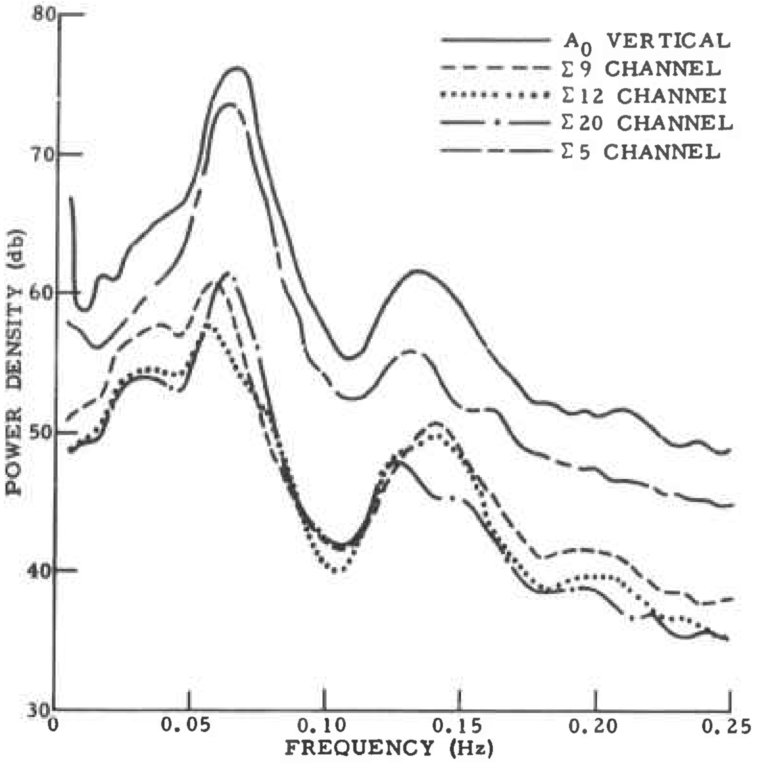

Figure III-5. Power-Density Spectra of Summation-Processor Outputs, 3 December

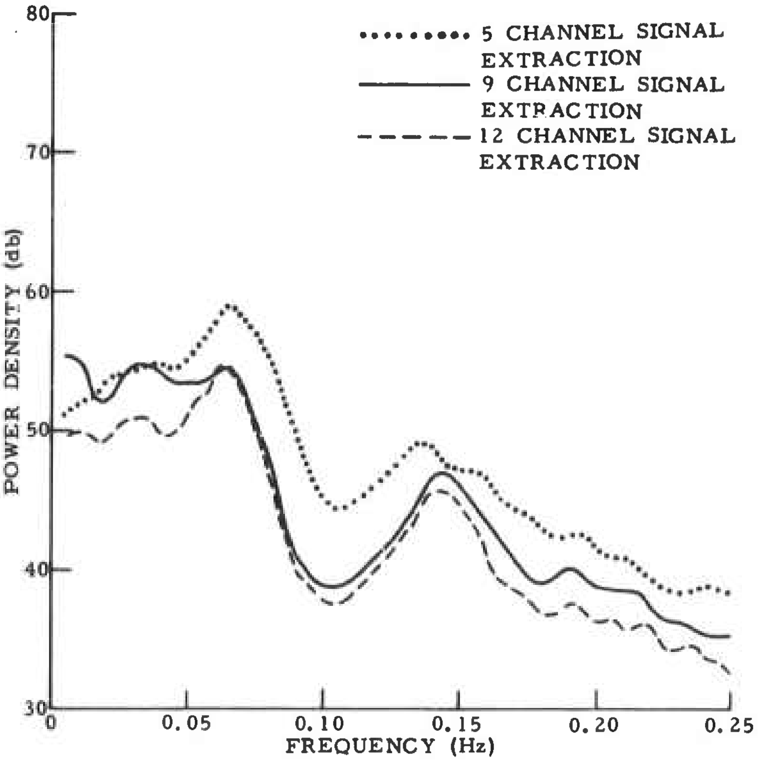

Figure III-6. Power-Density Spectra of 5-, 9-, and 12-Channel Signal-Extraction Outputs for 3 December

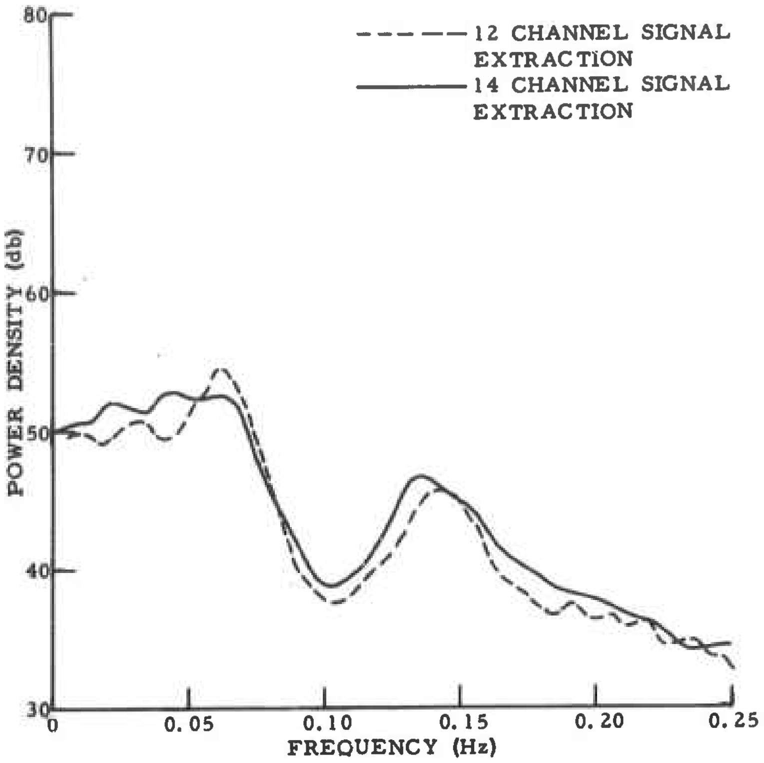

Figure III-7. Power-Density Spectra of 12- and 14-Channel Signal-Extraction Outputs for 3 December

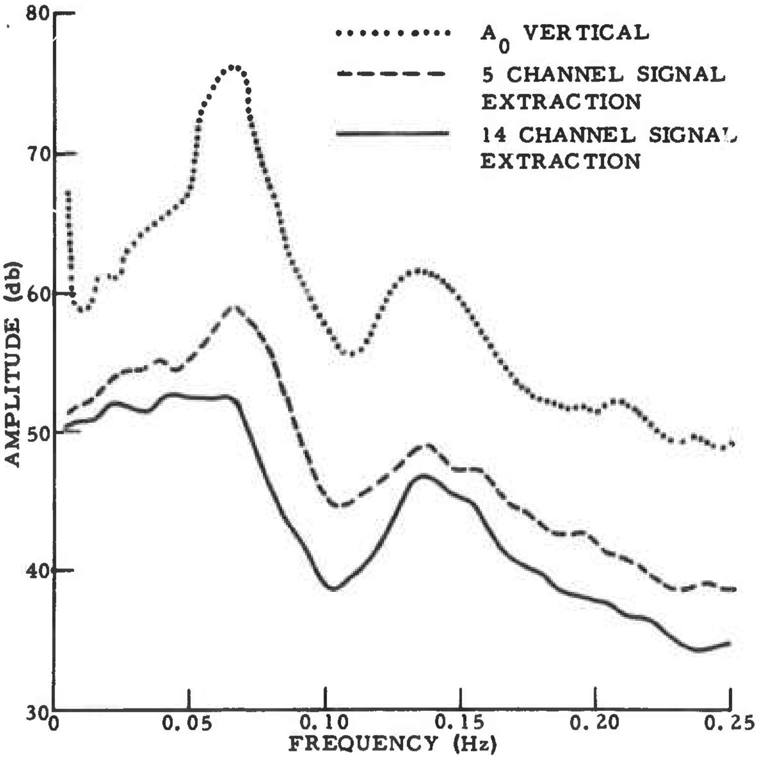

Figure III-8. Power-Density Spectra of Outputs of 5- and 14-Channel Signal-Extraction Filters, 3 December

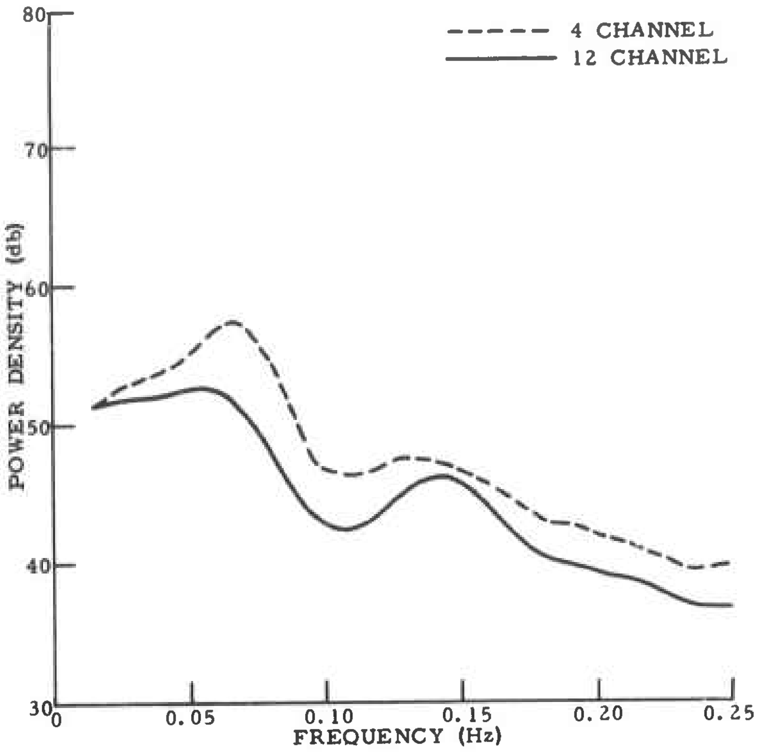

Figure III-9. Power-Density Spectra of Outputs from 4- and 12-Channel 19-Point Signal-Extraction Filters, 3 December

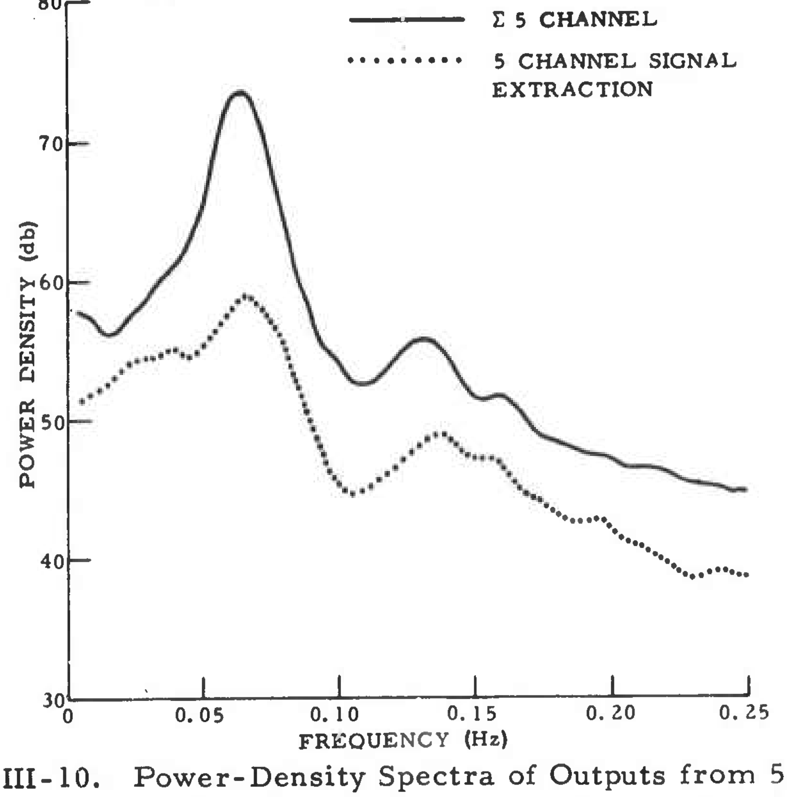

Figure III-10. Power-Density Spectra of Outputs from 5-Channel Straight-Summation and 5-Channel Signal-Extraction Filters, 3 December

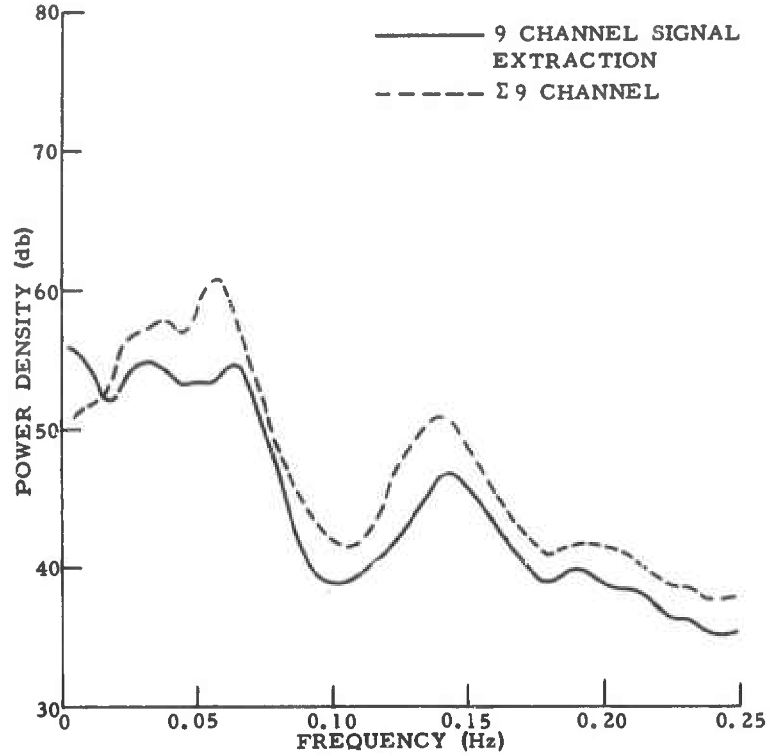

Figure III-11. Power-Density Spectra of Outputs from 9-Channel Summation and 9-Channel MCF Processors, 3 December

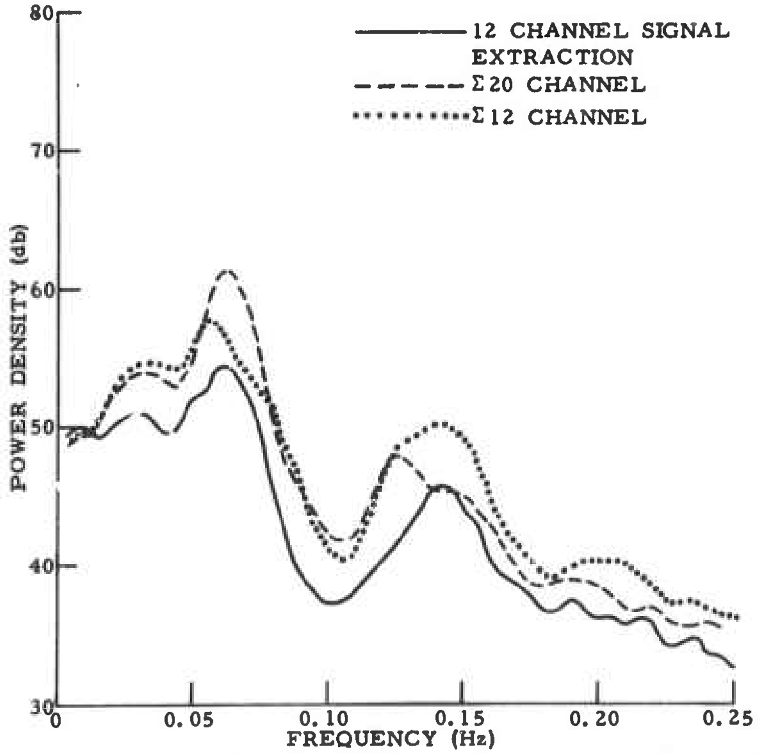

Figure III-12. Power-Density Spectra of Outputs from 12- and 20-Channel Summation and 12-Channel MCF Processors, 3 December

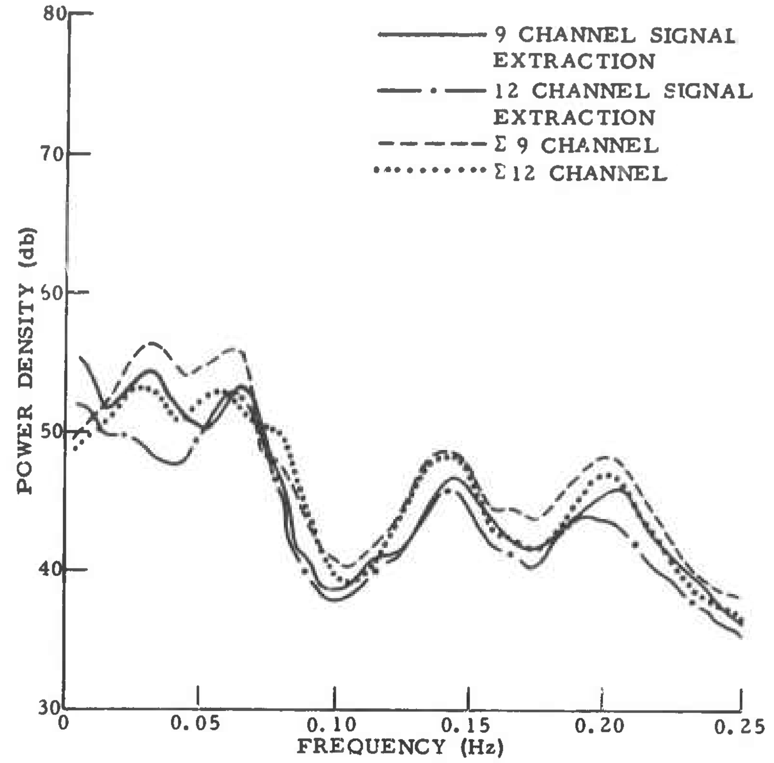

Figure III-13. Power-Density Spectra of Outputs from 9- and 12-Channel Summation and 9- and 12-Channel MCF Processors, 2 December

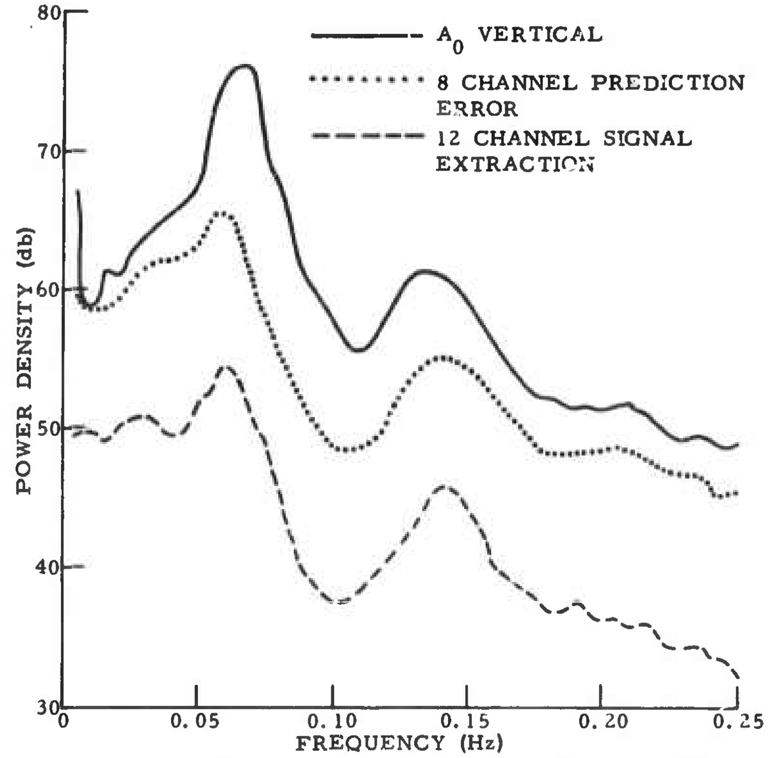

Figure III-14. Power-Density Spectra of 8-Channel Prediction-Error and 12-Channel Signal-Extraction Filters, 3 December

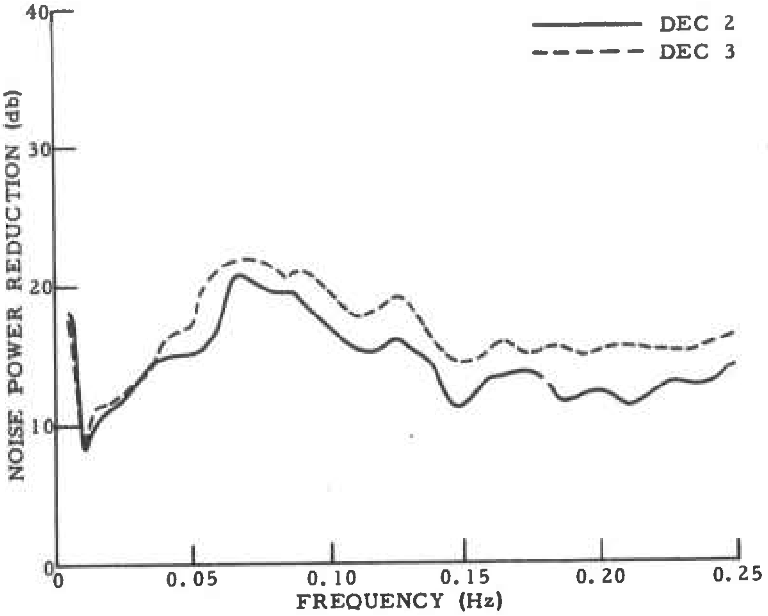

Figure III-15. Noise Power Reduction Relative to A0 Vertical of 12-Channel Signal-Extraction Filter, 2 and 3 December

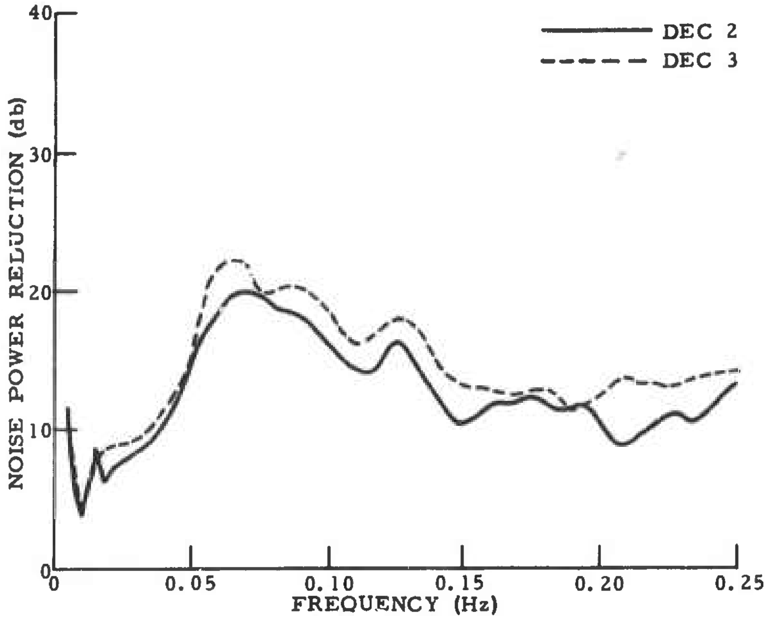

Figure III-16. Noise Power Reduction Relative to A0 Vertical of 9-Channel Signal-Extraction Filter, 2 and 3 December

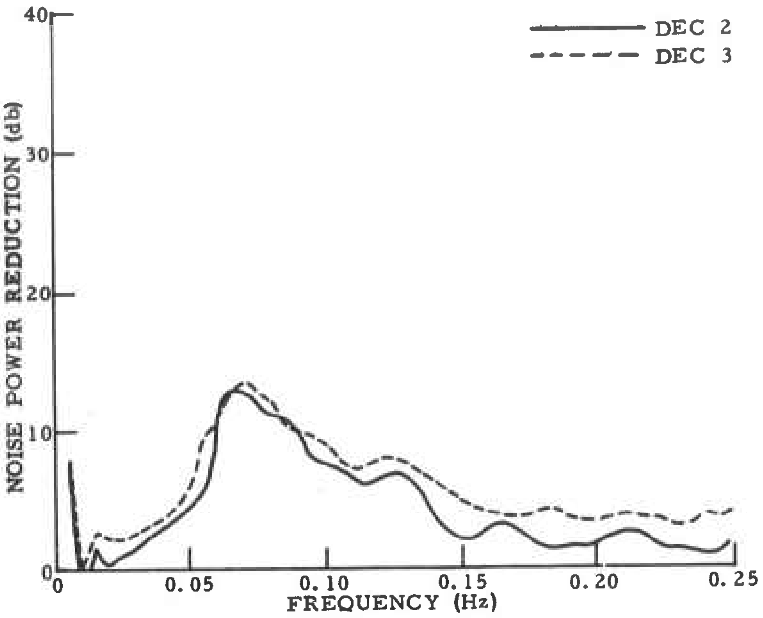

Figure III-17. Noise Power Reduction Relative to A0 Vertical of 8-Channel Prediction-Error Filter, 2 and 3 December

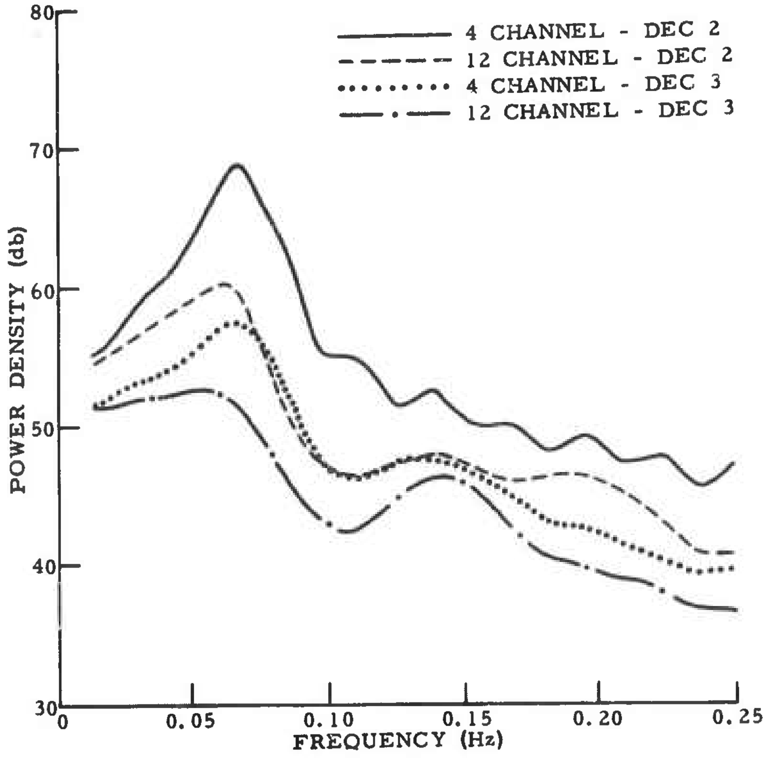

Figure III-18. Power-Density Spectra of 4- and 12-Channel 19-Point Signal-Extraction Filters, 2 and 3 December

Table II-1

PROCESSING SCHEMES

Processing Scheme	No. of Channels	No. of Filter Points	Sensors	Date Filter Designed from Data (1966)	Date Filter Applied to Data (1966)
Straight summation	5	-	A0 and B ring verticals	3 Dec	
	9	-	A0, C, and D ring verticals	2 and 3 Dec	
	12	-	A0, C, D, and E ring verticals (less E1)	2 and 3 Dec	
	18	-	All verticals except E1, F1, and F3	2 Dec	
	20	-	All verticals except F1	3 Dec	
Multichannel filter signal extraction with infinite-velocity mode	5	31	A0 vertical from A0 and B ring verticals	3 Dec	3 Dec
	9	31	A0 vertical from A0, C, and D ring verticals	3 Dec	2 and 3 Dec
	12	31	A0 vertical from A0, C, D, and E ring (less E1) verticals	3 Dec	2 and 3 Dec
	14	31	A0 vertical from A0 and B ring verticals and horizontals (less B2N)	3 Dec	3 Dec
	4	19	A0 vertical from A0 and B ring verticals (less B1)	3 Dec	2 and 3 Dec
	12	19	A0 vertical from A0 and B ring verticals and horizontals (less B1 vertical and B2 horizontal)	3 Dec	2 and 3 Dec
Multichannel prediction filter	8	19	Predict A0 vertical from A0 and B ring horizontals (less B2)	3 Dec	2 and 3 Dec

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13. ABSTRACT

Various infinite-velocity processing schemes were applied to two long-period noise samples recorded at the Montana LASA on 2 and 3 December 1966. Straight summation, multichannel signal extraction with an infinite-velocity signal model, and multichannel prediction filtering were applied to the presence of ambient noise. From the comparison of the various processing schemes, the 9-element array using multichannel filtering was found to be more effective than any straight summation for separating P-wave signals or surface modes widely separated from the noise and very nearly as effective as the 12-channel MCF. The vertical 5-channel MCF (A0 and B ring) is somewhat inferior to the 9-channel MCF (A0, C and D rings), but compares favorably with any of the summation processors. An MCF using the vertical channels in a signal-extraction mode and the horizontals in a prediction mode suppressed the noise as effectively as the vertical 12-channel MCF. Use of only the horizontals in a prediction mode gave significantly poorer noise rejection than other forms of processing. Of the summation processors considered, the 5-channel (A0 and B ring) is definitely the least effective in reducing noise. Of the remaining summation processors, none possesses a clear-cut advantage over the full frequency range. When judged by total power reduction, the three summation processors (9-channel, 12-channel and 18- or 20-channel) appear approximately equivalent.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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Noise Suppression						
Long-Period Noise						
Infinite-Velocity Processors						
Straight Summation						
Multichannel Signal Extraction						
Multichannel Prediction Filtering						

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