PART TEN

SIGNAL-TO-NOISE RATIO IMPROVEMENT TECHNIQUES

PART TEN

SIGNAL-TO-NOISE RATIO IMPROVEMENT TECHNIQUES

TABLE OF CONTENTS

		Page
List of Tables		10.iv
List of Figures		10.v
I.	SUMMARY	10.1
II.	BRIEF DESCRIPTION OF TECHNIQUES	10.2
	A. LINEAR PHASE FILTERING OF MULTICOMPONENT DATA	10.2
	B. REMODE	10.2
	C. DELAYED SUM	10.2
	D. WEIGHTED DELAY AND SUM	10.2
	E. MULTICHANNEL MAXIMUM LIKELIHOOD ARRAY PROCESSING	10.3
	F. MULTICHANNEL WEINER FILTERING	10.3
	G. SINGLE CHANNEL BANDPASS FILTERING	10.3
	H. SINGLE CHANNEL PREDICTION ERROR FILTERING	10.3
	I. MULTICHANNEL PREDICTION ERROR FILTERING	10.3
	J. MATCHED FILTERING	10.3
	K. DESIGN OF SUBARRAY CONFIGURATION	10.4
	L. BURIAL OF SENSORS	10.4
III.	SIGNAL PROCESSING FOR DETECTION OF A MINER	10.4
	A. SIGNAL-TO-NOISE IMPROVEMENT ON THE INDIVIDUAL SENSOR LEVEL	10.4
	B. SIGNAL PROCESSING AT THE SUBARRAY TERMINAL LEVEL	10.8

PART TEN

SIGNAL-TO-NOISE RATIO IMPROVEMENT TECHNIQUES

TABLE OF CONTENTS
(Continued)

		Page
	C. DETECTION PROCESSING ON THE FULL ARRAY LEVEL	10.10
IV.	SIGNAL PROCESSING EFFECTS RELATED TO LOCATION	10.11
V.	REFERENCES	10.15

PART TEN

SIGNAL-TO-NOISE RATIO IMPROVEMENT TECHNIQUES

LIST OF TABLES

Table No.	Title	Page
1	Comparison of Arrival Times	10.13

PART TEN

SIGNAL-TO-NOISE RATIO IMPROVEMENT TECHNIQUES

LIST OF FIGURES

Figure No.	Title	Page
1	Effect of Direct Summing on Waveform	10.12
2	Comparison of a Seismic Signal Before and After Passing Through the Westinghouse Matched Filter	10.14

PART TEN

SIGNAL-TO-NOISE RATIO IMPROVEMENT TECHNIQUES

Roy Greenfield

Pennsylvania State University

I. SUMMARY

During the detection phase, several procedures can be used to improve the signal-to-noise ratio (S/N).

- Subarrays of up to 10 seismometers should be used. The apparent failure to obtain improvement in S/N in the Westinghouse subarray work is probably due to excessive noise in the electronics. The spacings needed for sensors in the subarray must still be established.
- The sensors should be buried. Even burial to a few feet will probably give appreciable reduction of noise. A deeper burial will probably further reduce the noise; and, if the seismometers can be put below the weathered layer, the signal level will probably be increased. The reduction in noise by burial will be especially effective during high noise periods due to wind or rain.
- Before attempting detection, the waveforms should be bandpass filtered. The bandpass should go from 25 Hz to an upper frequency of 100 to 200 Hz. Further measurements with a low noise system must be done before the signal-to-noise ratio can be determined for the 100 to 200 Hz range. Any narrow band noise should be removed by notch filters.
- If noise levels differ among seismometers of a subarray, weights inversely proportional to the noise power should be applied to the seismometers.
- Automatic methods of screening data for possible signal arrivals should be developed, but the final determination that the signal on a subarray output appears to be from a miner should be made by an analyst. Detection of "signal" on several subarrays should be required for positive identification.

In the location phase, after detection:

- If repeated signals are received, they should be coherently added (stacked) to give as good a S/N as possible for use in determining signal arrival times, to be used in location computations. The miner should, if possible, repeat the signal 25 to 50 times.

It is probably not worth the increase in system complexity to implement such complex signal processing methods as multi-channel maximum likelihood filtering, linear particle filtering, or prediction error filtering. These will probably not give much signal-to-noise improvement. Matched filtering does not compress the body wave signals in time, and thus will not improve system performance any more than any suitable bandpass filter.

II. BRIEF DESCRIPTION OF TECHNIQUES

A. Linear Phase Filtering of Multicomponent Data [1]

The vertical component of a seismometer is added to a time shifted version of the horizontal component. With proper time shift this processing can accentuate a linearly polarized P wave arrival while suppressing eliptically polarized Rayleigh surface wave noise.

B. Remode [2] [3] [4]

A nonlinear method to accentuate linearly polarized portions of single sensor 3-component seismic data.

C. Delayed Sum

The output of each of a group of seismometers is delayed so that signals traveling at a selected horizontal phase velocity are added coherently. Note that the presently used system of subarray addition is a special case of delayed sum with zero delay between channels. Noise which is uncorrelated is reduced by a factor of 1/N in power where N is the number of seismometers. Coherent noise with phase velocities different from the direction at which the subarray is aimed is also reduced; the amount of reduction depends on the subarray pattern.

D. Weighted Delay and Sum

This processing is similar to delayed sum processing, but amplitude weighting of the channels is designed to maximize the suppression of coherent noise. The weights for this processing can be adaptively designed [5] to optimize suppression of a time varying noise field. The method is also useful if the noise level is unequal among channels.

E. Multichannel Maximum Likelihood Array Processing [6] [7]

The seismometer outputs are first time aligned for the horizontal phase velocity of the signal. Then an individual filter is applied to each channel. This processing is designed to operate where the signal is the same on each channel. Filter design requires extensive digital computation, and the filtering operation itself is costly in computer time. This form of processing can give large S/N improvement when a wideband signal is to be examined and coherent noise is present.

F. Multichannel Weiner Filtering [8]

This form of processing is similar to multichannel Maximum Likelihood Processing; however, the filters are designed for a signal modeled as a stationary multidimensional random process.

G. Single Channel Bandpass Filtering

Bandpass filtering can improve S/N if the major energies of the signal and noise are separated in frequency or if the signal is of narrower band than the noise.

H. Single Channel Prediction Error Filtering [9]

A filter is designed based on the noise to predict the noise ahead in time. The predicted noise is subtracted from the seismometer output, reducing the noise at the output of the filter. At the commencement of the signal the filter does not attenuate the signal, so the S/N ratio can be improved. This type of filter works best when the noise is fairly narrow band, so the filter can do a good job of noise prediction.

I. Multichannel Prediction Error Filtering [10]

The noise on each channel is predicted by applying filters to the noise on all the channels. This noise is subtracted from each channel and a trace produced for each channel. When the noise field is coherent between the channels, this procedure can give better noise reduction than the single channel prediction error filter.

J. Matched Filtering [11] [12]

If the signal waveform is known, a matched filter can compress in time a dispersed waveform by removing the dispersion effect, and thus give an improve-provement of S/N equal to the time bandwidth product. The matched filter is implemented by convolving the signal with a filter whose response is that of the known waveform. In addition, the application of a matched filter acts as

a bandpass filter, and thus gives an additional S/N improvement by rejecting out-of - signal-band noise.

K. Design of Subarray Configuration [13] [14]

A configuration of seismometers has a frequency dependent array response pattern. In areas of coherent noise the placement of sensors can be such as to put a low part of the beam response at the horizontal phase velocity of the noise. Spacing of the sensors far enough apart so the noise appears incoherent leads to a $1/\sqrt{N}$ reduction in noise amplitude, where N is the number of seismometers in the subarray.

L. Burial of Sensors [15] [16] [17]

If noise is composed of Rayleigh waves the noise amplitude falls off with depth; burial of sensors can lead to a decrease in noise amplitude. If noise is due to transient surface loading near the seismometer and has a certain correlation distance, then the noise level will also fall off with depth.

III. SIGNAL PROCESSING FOR DETECTION OF A MINER

Detection of a trapped miner by seismic means requires that the presence of a signal is identified in the presence of ambient background noise, and that this signal may be identified as the efforts of the miner. In this detection section we first consider what can be done on the subarray and individual sensor to improve S/N, then discuss how to use the subarray outputs to detect the miner's presence.

A. Signal-to-Noise Improvement on the Individual Sensor Level

Filtering methods which could be considered for application to a single seismometer output include Remode, Linear Phase Filtering of Multicomponent Data, Bandpass Filtering, Single Channel Weiner Filtering, Single Channel Prediction Error Filtering, and Matched Filtering. We now comment on the usefulness of these various methods.

1. Remode - This type of processing will not be useful for several reasons. First it must be designed and applied digitally. For application to 50 sensors at a sampling rate of 500 to 1000 samples per second the computation load would be far too large and not practical. Secondly the filter is designed on the

in-phase property of the P wave on the horizontal and vertical seismometers. From Westinghouse data, it appears that the arriving P wave is almost completely linearly polarized, but in the vertical direction, i.e., no horizontal (see Plot 49, Westinghouse Field Report No. 8).* Because of this, the Remode filter design would not work for P waves. However, it might work on part of the later arrivals. The reason for the vertical polarization is believed to be caused by the ray being bent toward the vertical as it traverses the low velocity material normally near the surface. Thirdly, it has not been established that the ambient noise is elliptically polarized as for a Rayleigh wave. Fourthly, implementation requires addition of horizontal sensors to each channel.

2. Linear Phase Filtering of Multicomponent Data - This type of filter might improve the S/N ratio, by subtracting a properly phase-shifted version of the horizontal from the vertical record. This could remove some of the elliptically polarized noise from the vertical. It is rather hard to estimate, without implementing the filtering on actual data, how well it will work. However, if the noise is predominantly Rayleigh wave from one direction, this method could work where Remode does not. This type of filtering could be done with analog equipment. Again, it would be required to have horizontal as well as vertical sensors.

3. Bandpass Filtering - Most of the signal energy is below approximately 200 Hz, and for many of the signals, it is below 100 Hz. (See Figures 2-11, 2-12, 2-13 of the Westinghouse Fy '72 Report.)* Westinghouse data suggests that significant seismic noise energy may exist out to frequencies of 500 Hz or more (see Figures 2-7, 2-8, 2-9). However, its contamination by electronic system noise lowered our confidence that the data really shows the presence of high frequency seismic noise. If the high frequency noise shown by Westinghouse is indeed seismic noise, bandpass filtering can increase the signal-to-noise ratio. Judging from these figures, the noise could be reduced by 3 to 6 db by low-pass filtering below 100-200 Hz with no significant loss of signal power. If signal detection is done by an analyst looking at clear records, he will do some bandpass filtering by eye so the low-pass filtering will not gain much. However, if detection is done by automatic threshold detection or by looking at a very compressed time scale visicorder record, it is important to remove the high frequency noise. The optimum cutoff

* Westinghouse Contract H0210063 with Bureau of Mines.

frequency will depend on noise spectra and an estimation of the signal spectra expected from the undetected signal. In any given situation a combination of theory and experimental data will allow us to estimate the signal spectra. In general, longer travel paths will lower the average frequency of the signal. It is clear from the Westinghouse results that at some mines narrow band noise sources are present. In such circumstances a notch (or narrow band rejection) filter should be used. Such filters can probably best be implemented with analog equipment.

4. Matched Filtering - Matched Filtering can give an improvement in S/N by compressing the energy of a dispersed waveform in time or by simply acting as a bandpass filter. Work was done by Westinghouse to evaluate matched filter performance. The filter clearly gives a significant S/N improvement. (See Figures 5 and 6, Appendix E of Westinghouse Report.)* However, the time-bandwidth product of the signal is not great and the matched filter does not seem to compress the signal in time. Therefore, it appears that the signal-to-noise improvement obtained by the matched filter is a result only of its bandpass filter characteristics. (The filter used does seem to be a reasonable bandpass filter to use.) It does not appear to predict the signal shape well enough to design a true matched filter, and it does not appear that the signal is dispersed sufficiently to warrant the attempt.

5. Single Channel Prediction Error Filtering - This type of filtering is most useful when the noise is fairly narrow banded. Then it is able to predict the noise ahead fairly well and subtract it from the trace. The spectral data show that the noise is wideband and thus it would not be expected that prediction error filtering could make a large S/N improvement. When tried by Westinghouse the Prediction Error filter provided essentially no improvement (see Westinghouse Fy '72 Report, Appendix E, page 29).*

6. Burial of Sensors - Large S/N improvement may be possible by burying the sensors. Very little information seems to be available in the literature for the frequency range of 30 to 200 Hz. (I also spoke to several people in exploration seismology and was told that because of time and costs, they do not normally bury geophones.) At the much lower frequencies of 1 to 5 Hz burial of a few hundred feet can give noise reductions of 20 to 40 db. (Seriff, A.J., et. al., Seismic Noise in Deep Boreholes, Contract No. AF 19 628-2785, Shell Development Co., Houston, Texas, June 21, 1965.)

---

* Ibid.

The noise reduction is greater on windy days. Since the surface noise level is high on windy days, even greater S/N gain can be obtained under this condition.

The amount of S/N gain obtainable by burial under various noise conditions cannot be estimated because we presently have no data on the spatial coherence or the depth variation. The theoretical discussion in the Westinghouse Report, Appendix C, discusses some of the possible reasons for the decrease in noise level. It is unfortunate that the experimental program discussed in Appendix C was terminated before data could be analyzed. Before any estimate can be made of S/N improvement, data must be analyzed to get empirical noise reductions and to get the spatial structure of the noise field. If the Westinghouse data is available, examination may allow some estimates of S/N improvements as a function of depth of burial. The only available results are from Section II-4.4 of the Westinghouse Report. Here noise reduction of 19 db at 30 Hz; 44 db at 100 Hz; and 55 db at 250 Hz were obtained for a seismometer in a 23-foot borehole relative to a surface seismometer. The data is from the USBM Safety Research Mine, and is for data taken during a hard rain (see Figure 2.4-4, Westinghouse Report).* addition there are indications (see Part Two, IV) that below a surface alluvium layer the signal may be of considerably higher amplitude than at the surface. It is also indicated that the energy spectra is shifted to higher frequencies for a seismometer below the alluvium. So it is clear that effects on the signal as well as noise reduction resulting from burial should be studied. The experimental and theoretical approach should be combined.

The range of depths which should be studied in the program should extend to as great a depth as it might be feasible to implant seismometers after a mine accident. If it is feasbile to lower or pre-place seismometers in the coal seams, the signals and noise levels in seams should be studied.

I will not at present make a complete discussion of the signal effects of burial. However, there are some conditions under which the signal may also be reduced in strength with burial which should not be overlooked. For example, a sinusoidal P-wave, vertically incident upon a perfectly reflecting interface in a lossless medium can produce a vertical standing wave pattern whose amplitude is given by A cos $[2\pi fz/V_p]$, whre z is depth. For f=100 Hz, and V_p=2000 ft/sec, the first null of this standing wave pattern will occur at z=5 ft.

---

* Ibid.

B. Signal Processing at the Subarray Terminal Level

1. Delayed Sum Processing - This type of processing can give gains of 1/N in power (N is number of sensors in the subarray) for 'random' noise, and a gain depending on the beam pattern for coherent noise. Signal loss, because of differences in signal shape must be considered also.

Let us assume that the traces are time aligned so the signals of interest add. The delayed sum output is

$$F(t) = \sum_{i=1}^{N} f_i(t) \qquad (1)^*$$

where f_i (t) is the individual sensor output. If the noise of total power, P_{in}, is composed of a coherent fraction C (in power) then the fraction of noise power which is incoherent is (1-C). (We caution that the coherent portion of noise depends on the sensor spacing. For example all noise will appear coherent if sensors are close together, and all noise will appear incoherent if the sensors are moved far enough apart.) If the beam response of the subarray reduces the coherent noise power by a factor of G then the noise on the output is

$$P_{out} = \frac{1}{N} \cdot P_{in} \cdot (1-C) + P_{in} \cdot C \cdot G \qquad (2)$$

If the subarray is large enough the noise reduction will always go to 1/N in power. Failure to obtain 1/N gain is only an indication that the noise is coherent to some extent. The Westinghouse experience with subarray summing is not representative of the improvements that can be achieved with this technique.

Measurement of the noise spatial coherency [13] between sensors as a function of separation can be used to decide the necessary separation between sensors to get close to 1/N noise reduction, larger coherence distances demanding larger separations. The data taken to date above coal mines is insufficient to form a basis upon which I can make a recommendation of subarray element spacing, because the subarray design must reflect the noise field encountered there.

There is another consideration if the distance over which the noise is coherent forces us to a large diameter subarray. If the array is not small

* References to Figures, Table, and Equations apply to those in this Part unless otherwise noted.

compared to the signal horizontal wavelength, signal amplitude decreases and distortion will occur unless the subarray is steered toward the signal. Let us assume that we form the sum with no time delays for a signal of 10,000 ft/sec horizontal phase velocity, and frequency of 100 Hz. Typically an array with seismometers within a circle of diameter d will have less than 3 db signal reduction if $\frac{d.f}{V_n} < 0.25$. Thus d could be as great as 25 ft. for less than 3 db signal loss. In the detection mode, we do not know the direction and horizontal phase velocity of the signal. If it were necessary to go to a larger subarray diameter, or if the horizontal phase velocity were less than 10,000 ft/sec, it might be necessary to form a few delayed sum beams, perhaps 5 at each subarray, in order to prevent excessive signal loss. This type of processing can be implemented with analog equipment.

2. Weighted Delay and Sum - If the noise is unequal and uncorrelated on the seismometers of a subarray, then unequal weight will give a greater noise reduction than equal weighting. This type of weighting is called Brennen combining. If the noise is in the main coherent and coming from a small number of fixed sources, unequal weightings of the seismometers can be used to shape the subarray beam to reject the coherent noise. This type of processing can probably be implemented with analog equipment. [18]

3. Subarray Configuration - If the noise is in the main propagating at a single velocity, such as the Rayleigh wave velocity, proper construction of the subarray geometry may produce an important noise reduction. Namely, the diameter of the array can be chosen to give a near null at the Rayleigh wave velocity. This has been well discussed in the Westinghouse Report. We note that in practice it may be inconvenient to first set up sensors to determine noise properties, then redeploy the sensors to give a better subarray beam pattern.

4. Methods of Multichannel Filtering - It was suggested in Appendix E of the Westinghouse Report that complex signal processing methods might be useful. Such methods include Multichannel Maximum Likelihood, Multichannel Weiner, and Multichannel Prediction Error Filtering. I will not go into detail; however, I do not feel these methods would be appropriate for subarray or full array application. These methods require for S/N improvement that the noise be highly coherent and time stationary, that the signal be highly coherent between sensors,

and that the gains on the various channels be carefully matched. It is probable that some or all these conditions will be violated. These methods require a very large computing facility for the sampling rate under question.

5. Repetition of Source Blows - Summation of repeated source blows will always reduce the noise power by 1/N. This was borne out in Westinghouse's work. They also showed that when the traces could be properly time aligned no significant signal loss occurred. It was also shown that if the traces could not be properly aligned some signal loss occurred, so the S/N gain was not as great as N in power. (See Figure II 2-15, Westinghouse Report.)

In the detection mode if the miner's signal has not been identified on any channel, it will not be possible to time align successive signals for S/N improvement. Thus the measurement of S/N gain will not be available when needed most. However,if a signal is seen at intervals on a single subarray output the method can be used to determine if the signal is on other subarray outputs. This could be useful to verify that the signal on the best channel is in fact due to a signaling miner and not to some unimportant signal source, such as a banging door, near the one subarray.

C. Detection Processing on the Full Array Level

We start with the signal outputs from the separate subarrays. I do not think that any sort of multichannel filtering will be useful for combining the subarray outputs. It will be found, I'm sure, that the noise is incoherent between subarrays. Even simple delay and sum processing will not be practical. There could be as much as 200 ms. delay between subarray arrival times. This delay is not known before detection. To coherently sum sensors with 100 Hz energy they must be properly aligned to within 1 m sec. or better. Thus there are 200 possible relative delays between each pair of subarray outputs. It is clear that delay and sum would impose an impossible computational load.

In the detection mode the array processor must handle a great deal of data. If the processing is done digitally a sampling rate on the order of 1000 samples/sec per subarray is needed. Thus 7000 samples per sec are coming in. Thus it is probable that the signal processing for detection must be fairly simple. The most reasonable way to detect the miner is to use a criteria that a signal be detected on several subarrays within some time window representing the estimated travel time differences between the subarrays. This will be useful if the S/N

is not much greater on one of the subarrays than on the others. By use of this 'coincidence detection', a detection can be made at a lower signal threshold for a fixed 'false alarm' rate than would be possible for a single subarray.

The threshold that should be used for a detection on each subarray signal should be set at 3 times the RMS noise level on that channel. If the noise level is not time stationary, the level should be set by, for example, setting the threshold at 3 times the RMS noise level over the last 30 seconds. (Geotech and Lincoln Laboratories have done extensive work on detection criteria for nuclear detection.)

As possible signals are detected, the data for these detections should, of course, be saved for use in the location process.

IV. SIGNAL PROCESSING EFFECTS RELATED TO LOCATION

After a miner has been detected, portions of the data containing signals can be reprocessed to improve arrival time estimates. The summing up of repeated source blows is useful for improving signal to noise.

The summing up of the seismometers of a subarray improves S/N. However, if direct sum with no delays is used, then some slight signal distortion can occur since the signals are added with slight misalignment. A simple sketch of this effect is given in Figure 1. This summing will in general make the first break somewhat less sharp and will distort the waveform slightly. The arrival time reading error which could result might be on the order of 2 ms. It is difficult to say if the noise reduction would compensate for this. The magnitude of the signal distortion will increase as the size of the subarrays are increased. One means of alleviating this effect would be to put in a delay line for each seismometer after the approximate location is found. This would align the traces in the subarray sum.

The matched filter proposed in Appendix E* has some advantage. The S/N ratio is improved. However, as stated previously this is due to the bandpass filtering effect whereby the filter removes high frequency noise. The matched filter does not get S/N improvement by compressing a dispersed wave train. Filtering by the filter constructed in Figure 3 of the Westinghouse Fy '72 Report, Appendix E, changes the signal waveform. Here the signal distortion is not great, as shown

* Westinghouse Fy '72 Report, Contract H0210063.

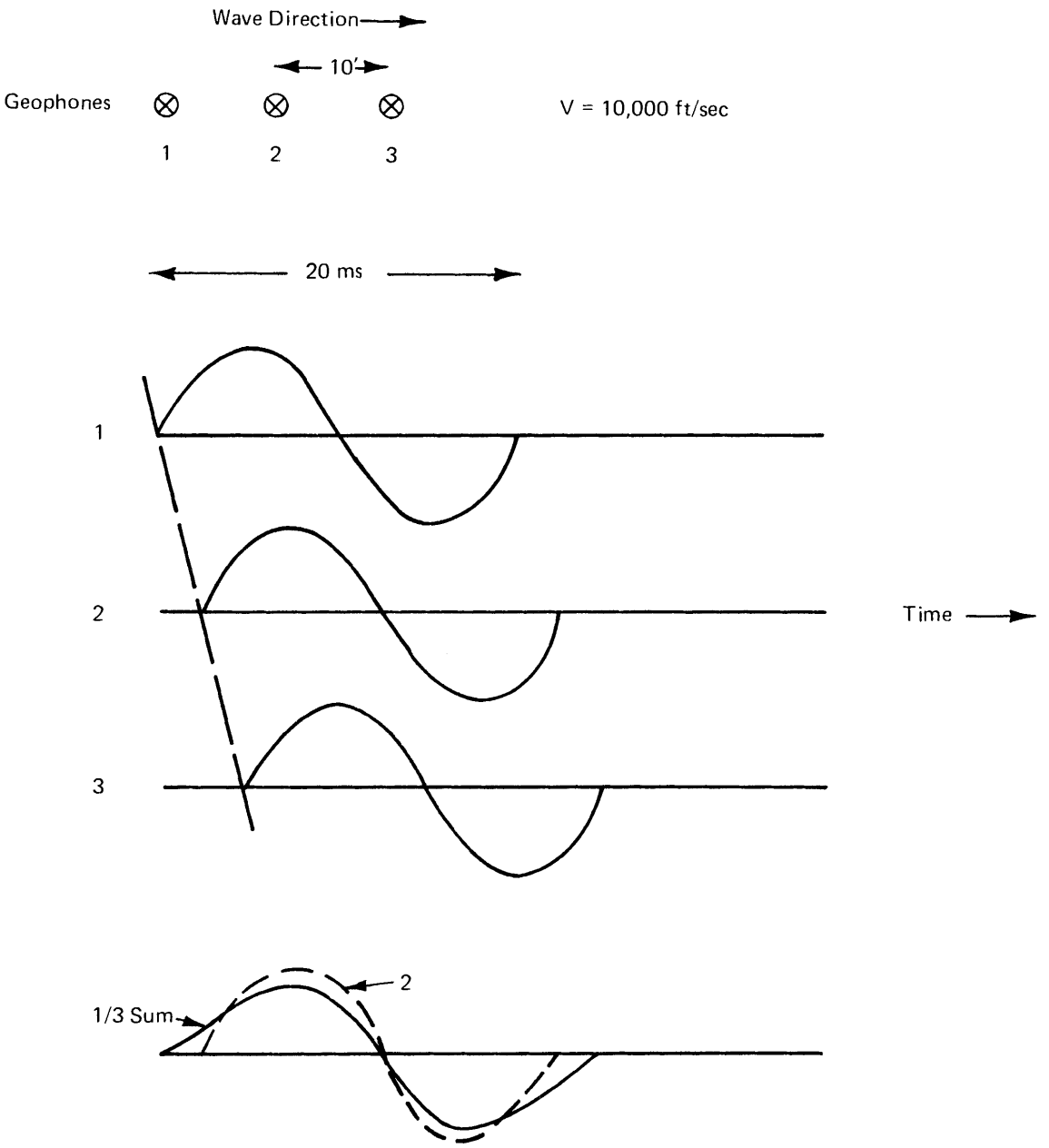


FIGURE 1 EFFECT OF DIRECT SUMMING ON WAVEFORM

in Figure 2. However, an example taken from [11] shows how a slightly different matched filter can change the output waveform and reverse polarization. One set of Westinghouse data was available to determine how time picks on the unfiltered data compared to the picks made on matched filtered data. In Appendix E arrival times were picked on match filtered data, (Appendix E, Table 1). The analyst's time picks on this data, before matched filtering, were found on the input to the computer location program in Field Report No. 4.* For both sets of time picks we calculated the arrival times relative to channel 6. (Only four channels were picked in Appendix E.) Table 1 shows the comparison.

TABLE 1 - COMPARISON OF ARRIVAL TIMES

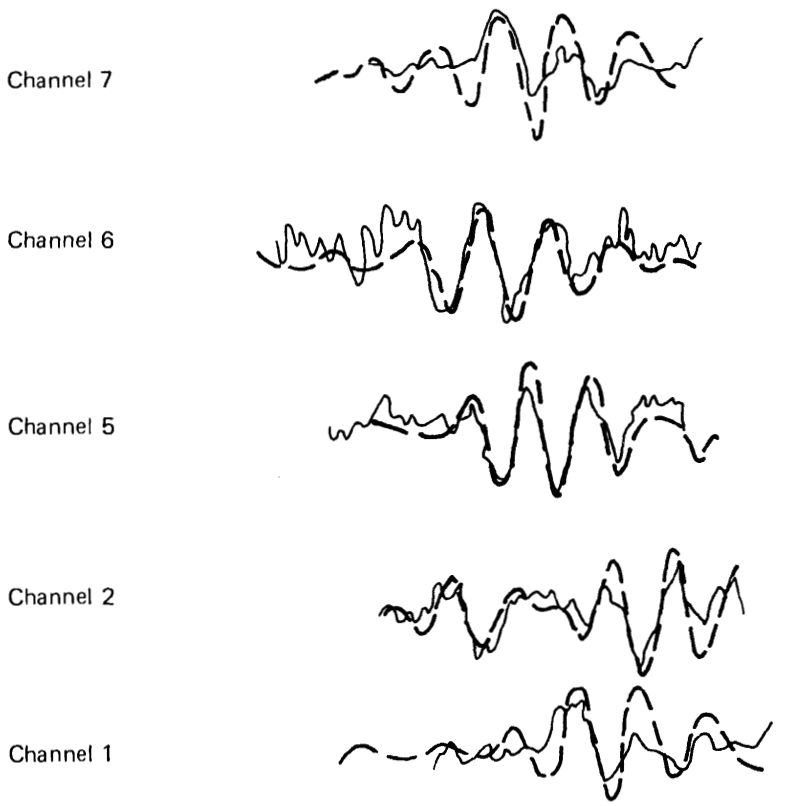
Channel Number	A-T Matched Filter Signal	A-T Field Report 4	Difference
1	16.25 m. sec.	12.8 m. sec.	+3.4 m. sec.
5	10.30 m. sec.	9.7 m. sec.	1.6 m. sec.
7	14.25 m. sec.	16.3 m. sec.	-2.1 m. sec.

Thus we feel that the time picks from the matched filter output may be in error on the order of 2 m. sec. This is to be contrasted to the RMS scatter of time picks on the matched filtered data of from 1.00 to 0.71 m. sec. (ms) given in Westinghouse, Appendix E.

In general, except in very high signal to noise situations where first breaks can be seen, an error of 1 or 2 ms will probably have to be tolerated. However, if a half cycle is missed, this will introduce approximately a 10-15 ms error. Data processing should probably concentrate on methods to avoid this missing of a half cycle. In particular it may be helpful to determine the polarization to be expected at each site when we have a rough fix on the source location.

---

* Westinghouse Contract H0210063.



(From Figures 5 & 6 of Appendix E of Westinghouse Report)

——— Raw Trace
— — Matched Filtered Trace

FIGURE 2 COMPARISON OF A SEISMIC SIGNAL BEFORE AND AFTER PASSING THROUGH THE WESTINGHOUSE MATCHED FILTER

V. REFERENCES

1. Mercado, E.J., Linear Phase Filtering of Multi Component Seismic Data, 33, 926, 1968
2. C.B. Archambeau, E.A. Flinn, and D.G. Lambert, "Detection, Analysis, and Interpretation of Teleseismic Signals 1. Compressional Phases From the Salmon Event," J. Geophys. Res., Vol. 71, pp. 3483-3501, July, 1966.
3. C. Mims and R. Sax, "Rectilinear Motion Detection (RE-MODE)", Teledyne, Inc., Alexandria, Va., Seismic Data Lab Report 118, March 1965.
4. C.B. Archambeau and E.A. Flinn, "Automated Analysis of Seismic Radiation for Source Characteristics," Proceedings of the IEEE, Vol. 53, pp. 1876-1884, Dec. 1965.
5. Lacoss, R.T., Adaptive Combining of Wideband Array Data for Optimal Reception, IEEE Geoscience Electronics, GE-6, 78-86, 1968.
6. J. Capon, R.J. Greenfield and R.T. Lacoss, "Long-Period Signal Processing results for the Large Aperture Seismic Array," Geophysics, Vol. 34, pp. 305-329, June 1969.
7. J. Capon, R.J. Greenfield, R.J. Kolker, and R.T. Lacoss, "Short-Period Signal Processing Results for the Large Aperture Seismic Array", Geophysics, Vol. 33, pp. 452-472, June 1968.
8. Backus, M.M., J.P. Burg, R. Baldwin, and E. Bryan, Wideband Extraction of Martle P Waves from Ambient Noise, Geophysics, 29, 672-699, 1964.
9. Wiener, N., "Extrapolation, Interpolation, and Smoothing of Stationary Time Series", MIT Press, Cambridge, Massachusetts, 1949.
10. Clairbout, J.F., Detection of P Waves from Weak Sources at Great Distances, Geophysics, 29, 197 , 1964.
11. Capon, J., R.J. Greenfield, and R.T. Lacoss, Long Period Signal Processing Results for the Large Aperture Seismic Array, Geophysics, 34, 305-329, 1969.
12. Alexander, S.S., and D.B. Rabenstine, Detection of Surface Waves from Small Event at Teleseismic Distances, Seismic Data Lab, Report 175.
13. J. Capon, R.J. Greenfield, and R.T. Lacoss, "Design of Seismic Arrays for Efficient On Line Beamforming," Lincoln Laboratory Technical Note, 1967-26, 27 June 1967.

14. R.T. Lacoss, J. Capon, R.J. Greenfield, "Preliminary Design of a Long Period Seismic Array for Norway," Lincoln Laboratory Technical Note, 1968-4, 24 January 1968.

15. Shappee, R.M., and E.J. Douze, Final Report Project VT/5051, Deep Well Research, Contract No. AF 33 (657)-13668, Geotech, Garland, Texas, 2 February 1967.

16. Seriff, A.J., J.H. Rosenbaum, C.J. Velzeboer, and R.J. Haase, Seismic Noise in Deep Boreholes, Contract No. AF 19(628)-2785, Shell Development Co., Houston, Texas, June 21, 1965.

17. G.G. Sorrells, John A. McDonald, Z.A. Der and Eugene Herrin, "Earth Motion Caused by Local Atmospheric Pressure Changes", Geophys. J. Riastr. Soc., Vol. 26, pp. 83-98, 1971.

18. Gangi, A.F., A Space Time Filter for Seismic Models, Presented, SEG, November 8, 1966.