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TR 81-12

TECHNICAL REPORT NO. 81-12
FINAL REPORT
SEISMIC SIGNAL DETECTION ALGORITHMS

TELEDYNE GEOTECH

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This report covers the procedures undertaken and the results obtained during an 18-month program to implement and test an automatic seismic event detection algorithm that is based on the Walsh transform. The algorithm was successfully implemented and tested on a Z80A-based microcomputer, and the system was placed in operation at the Norwegian Seismic Array (NORSAR) for on-line evaluation. The results of the system operation and effectiveness is presented. Also included is a report of the performance of the detection algorithm in off-line tests utilizing standard tapes prepared under AFTAC/VSC supervision.

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TECHNICAL REPORT NO. 81-12

FINAL REPORT

PROGRAM TITLE

SEISMIC SIGNAL DETECTION ALGORITHMS

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FINAL REPORT
SEISMIC SIGNAL DETECTION ALGORITHMS

1. SUMMARY

This report covers the procedures undertaken and the results obtained during an 18-month program to implement and test an automatic seismic event detection algorithm that is based on the Walsh transform. The goal of the program was to develop a microprocessor-based system with an on-line event detection capability and a false alarm rate comparable to that now being achieved off-line in large computer systems. Interest in such a project was initiated in 1979 when Tom Goforth and Eugene Herrin, with AFOSR and Teledyne corporate support, developed an algorithm which was capable of implementation on a microprocessor and for which off-line studies indicated excellent detection properties. The Goforth-Herrin algorithm takes advantage of the dyadic and symmetric properties of a set of orthonormal functions described by Walsh (1923) and utilizes an L-1 normative representation of the noise background history. Since the amplitude of any Walsh function has values of only +1 or -1, the Walsh transform can be accomplished in a computer with a series of shifts and fixed point additions. The savings in computation time relative to the Fourier transform makes it possible to compute the Walsh transform and to perform pre-whitening and bandpass filtering in the Walsh domain for use in real time signal detection.

A comprehensive analysis was made of the computer requirements necessary to implement the algorithm for multi-channel operation. On the basis of requirements of core storage, execution speed, precision, and low cost, the North Star Horizon computer was selected as the basic unit of the detection system. The Horizon computer is a complete microcomputer system with integrated floppy disk memory. It has a Z80A processor board which operates at 4 mhz and has its own programming language. The detection algorithm was implemented on the Horizon system such that it can operate on up to 10 data channels (20 sps) simultaneously. The multiplexer, programmable amplifier, and analog-digital converter are packaged with the microprocessor in a 50.8 x 20.3 x 48.3 cm case. Control and output of the detection system are provided by the Horizon CRT/keyboard and by a Texas Instruments OMNI 800 Printer. A Helicorder is used to provide a visual record of the upcoming data.

The on-line evaluation of the detector was accomplished at the Norwegian Seismic Array (NORSAR). NORSAR was selected for use in the evaluation because the detector performance on individual channels could be conveniently compared with the performance of the overall array. Three short-period seismographs in the 03C sub-array (01, 03, and 04) were selected to provide a 3-channel input to the detection system. Sub-array 03C is the most reliable of the sub-arrays in terms of minimal outage time, and it is intermediate in terms of detection capability. Sites 01, 03, and 04 form a triangle with sides 6 to 8 km long, a sufficient separation to assure incoherence of the short-period noise background but not so great as to produce significant "step-out" across the array for teleseismic P-waves. Detection analysis was performed independently on the 3 channels, with a detection being called if all channels raised a flag during the same 3.2 sec analysis window. The standard to which the Walsh system was compared is the NORSAR Detection Processor, in which the event detection procedure

consists essentially of a continual signal-to-noise ratio test on each of 322 real time array beams. Whenever a short-term average (STA) exceeds a long-term average (LTA) by a factor of 3 a certain number of consecutive times, a detection is declared on that beam. A computer plot is made of the segment of the beam seismogram in which the signal is called. These plots were useful in determining whether a NORSAR Detection Processor detection was a valid seismic signal or a false alarm. A continuous Helicorder record was made of the 03C-01 input to the Walsh detection system. False alarms and detections on the Walsh system were determined by visual analysis of the Helicorder records. With a unanimous vote required for a detection, the Walsh detection system operated on the 3 channels of the 03C sub-array from 18 October 1980 through 04 January 1981. During this period NORSAR detected a total of 1041 events with a false alarm rate of 0.70/hour, while the Walsh system detected 1347 events with a false alarm rate of 0.21/hour. If the total number of events is assumed to follow a log N = A -1.0 m_b distribution, then the 3-channel Walsh system shows a detection threshold 0.1 magnitude unit lower than the NORSAR beams. However, the lower detection threshold of the Walsh system is influenced considerably by the general insensitivity of the NORSAR beams to local and regional events.

A rigorous off-line evaluation of the Walsh detection algorithm was conducted by implementing the algorithm on a DEC 11/780 computer and using standard test tapes furnished by the Seismic Data Analysis Center. Two test tapes were evaluated. The first contained over 22 hours of NORSAR data samples at 10 sps. The second contained over 20 hours of Pinedale data samples at 20 sps. The noise data from both stations were randomized in phase, and test signals were buried in the noise every nine minutes at various signal-to-noise ratios (S/N). There was a total of 260 signal occurrences. The results indicated that the Walsh system could detect about 80% of all signal occurrences at an S/N of 1/2 while operating at a false alarm rate of about 1 per hour. The detection percentage increased to 95% as the false alarm rate approached 9 per hour. No attempt was made during the tests to optimize the Walsh detector for the particular samples under analysis. That is, initial estimates for the whitening weights, the processing passband, and long-term noise characteristics were maintained throughout the analysis. A subsequent study to determine optimum values for these parameters indicated that the use of time adaptive whitening weights, when combined with a 7-minute (rather than 14-minute) period to characterize the noise history, halves the false alarm rate at the 80% detection level.

Finally, all components of a ROM-based Walsh detection system were assembled and tested for operational stability. The system is designed to operate unattended at a remote location. It utilizes a single channel detector to flag potential seismic events and multiplexes a step function onto a telephone line with the analog data to mark detections. The system could also, if desired, set a flag to accumulate digital waveform data during the course of an event.

A detailed discussion of the conduct and results of the study is included in the three Semi-Annual Technical Reports which are presented as Appendices I, II, and III.

2. CONCLUSIONS

The on-line evaluation at NORSAR indicated that the microprocessor-based Walsh detection system, operating on these channels, is comparable in detection capability to the NORSAR Detection Processor operating on 322 beams, while running at a false alarm rate of about one-third that of the Detection Processor. It should be noted that NORSAR does not use local and regional beams and that many of their missed signals are in this category. If the signal population were limited to teleseisms, NORSAR's detection threshold would probably be lowered relative to that of the Walsh system, but such a comparison cannot be made without confirming the locations of all the events detected by the two systems.

The off-line evaluation using SDAC standard test tapes provided a basis of comparison between the Walsh detector and various other automatic signal detectors. Neither the MARS, Shensa, nor the TI power level detector has as low a detection threshold at a given false alarm rate as does the Walsh system. SDAC tested a variety of detection algorithms, including 27 different versions on the NORSAR data and 32 on the Pinedale data. Of the total of 59, 6 performed better than the Walsh, 8 about the same, and 45 worse. While the Walsh algorithm showed great consistency in performance between NORSAR and Pinedale data, the other detectors were quite erratic; comparable runs showed neither the same detection capability nor the same false alarm rate. The stability in the performance of the Walsh system is due to the robust nature of the statistic used for detection. It has nothing to do with the properties of the Walsh transform, as was demonstrated by the erratic behavior of the Shensa detector when the Walsh transform was utilized instead of the Fourier transform.

3. RECOMMENDATIONS

Because of the high detection capability, low false alarm rate, speed, and minimal computer requirements of the Walsh seismic event detection system, we recommend that it be given serious consideration for applications where detection is best accomplished at the recording site. Such situations might occur when the sensor is located in a hostile environment and continuous transmission of data is not feasible (e.g., ocean-bottom) or when high data rates require that only signal waveform data be transmitted (e.g., high frequency arrays).

One factor remains to be evaluated in the single channel implementation of the detector. For a signal detector to be optimum in a mathematical sense, the spectrum of the signal must be known. Since the signal spectrum is not known in general, the Walsh algorithm assumes it to be white within some passband, the corners of the passband depending on the recording station. However, if it were desired to optimize the detector for a particular class of signals (e.g., explosions at teleseismic distance), it is quite possible that an estimate of the expected signal spectrum would prove superior to the assumed white spectrum. This should be evaluated.

The multi-channel voting detector has been shown to be significantly better than the single channel application, particularly in reducing the false alarm rate. However, the optimal mode of multi-channel utilization is not yet known. Data from arrays such as the 13-element station in Alaska should be analyzed to determine:

a. The relationship between voting false alarm rate values and array element spacing.

b. The relationship between the probability of a false alarm and the probability of missing a small event by requiring N out of M elements in the vote.

c. The comparative detection capabilities of a single channel detector operating on an array beam and multi-channel vote operating on the elements of the array.

APPENDIX 1

TECHNICAL REPORT NO. 81-7

SEMI-ANNUAL REPORT FOR THE PERIOD
15 February 1980 through 15 August 1980

TECHNICAL REPORT NO. 81-7

SEMI-ANNUAL REPORT FOR THE PERIOD
15 February 1980 through 15 August 1980

PROGRAM TITLE

SEISMIC SIGNAL DETECTION ALGORITHMS

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SEMIANNUAL REPORT FOR THE PERIOD
15 February 1980 through 15 August 1980

SEISMIC SIGNAL DETECTION ALGORITHMS

1. INTRDOUCTION

This report covers progress made during the period 15 February 1980 through 15 August 1980, on a contract to implement and test an automatic event detection algorithm that is based on the Walsh transform. The objective of the program is to develop a microprocessor system with event detection capabilities and false alarm rates comparable to that now being achieved in large computer systems. Interest in such a project was initiated in 1979 when Tom Goforth and Eugene Herrin, with AFOSR (Contract F49620-76-C-0031) and Teledyne Corporate support, developed an algorithm which was capable of implementation on a microprocessor and for which off-line studies indicated excellent detection properties. During the present reporting period the Goforth-Herrin algorithm was successfully implemented and tested on a Z80A-based microcomputer, and the system was placed in operation at the Norwegian Seismic Array (NORSAR) for on-line evaluation.

1.1 THE GOFORTH-HERRIN ALGORITHM

The Goforth-Herrin algorithm takes advantage of the dyadic and symmetric properties of a set of orthonormal functions described by Walsh (1923). The first nine orders of the Walsh set are shown in figure 1. Since the amplitude of any Walsh function has values of only +1 and -1, the Walsh transform can be accomplished in a computer with a series of shifts and fixed point additions. The savings in computation time relative to the Fourier transform makes it possible to compute the Walsh transform and to perform pre-whitening and bandpass filtering in the Walsh domain with a microprocessor for use in real time signal detection.

A schematic of the algorithm is shown in figure 2. Digital data are analyzed sequentially in 64-sample (3.2 sec) windows with a 32-sample (1.6 sec) overlap. After the data in the analysis window are transformed, the Walsh coefficients are weighted so as to whiten the long-term Walsh spectrum of the noise. The weights are factors such as 1/8, 1/4, 1/2, 3/4, and 1, which can be applied by shifts and fixed point addition. The coefficients are further weighted by zero or one to isolate the expected sequency band of the signal. The absolute values of the coefficients rather than their squares are summed because the absolute value appears to be a more stable parameter for the non-normally distributed value; it is also much faster to compute. The detection threshold, which is computed from the distribution of the previous 512 sums of absolute values, is defined by

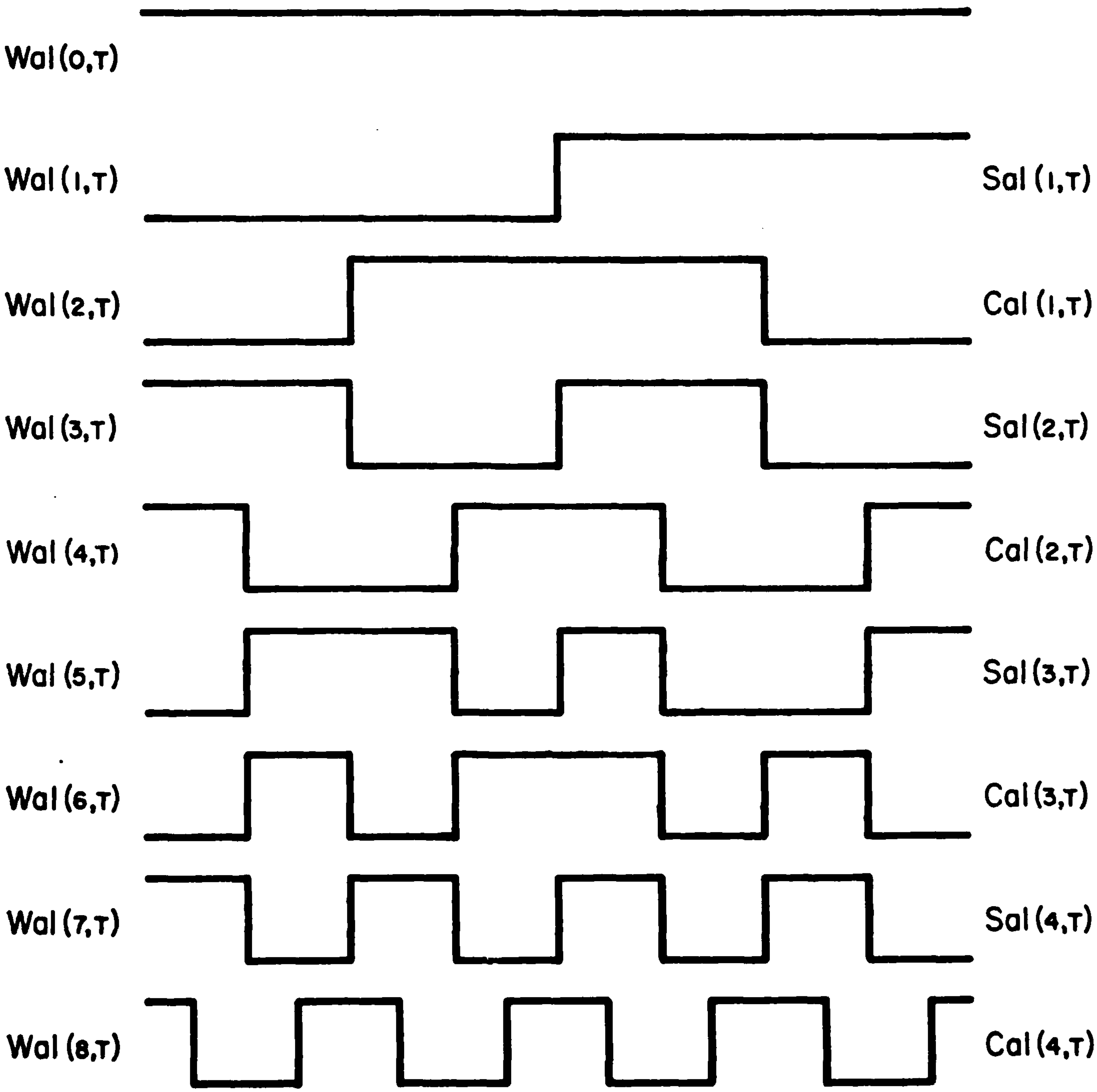

Figure 1. First nine orders of Walsh functions

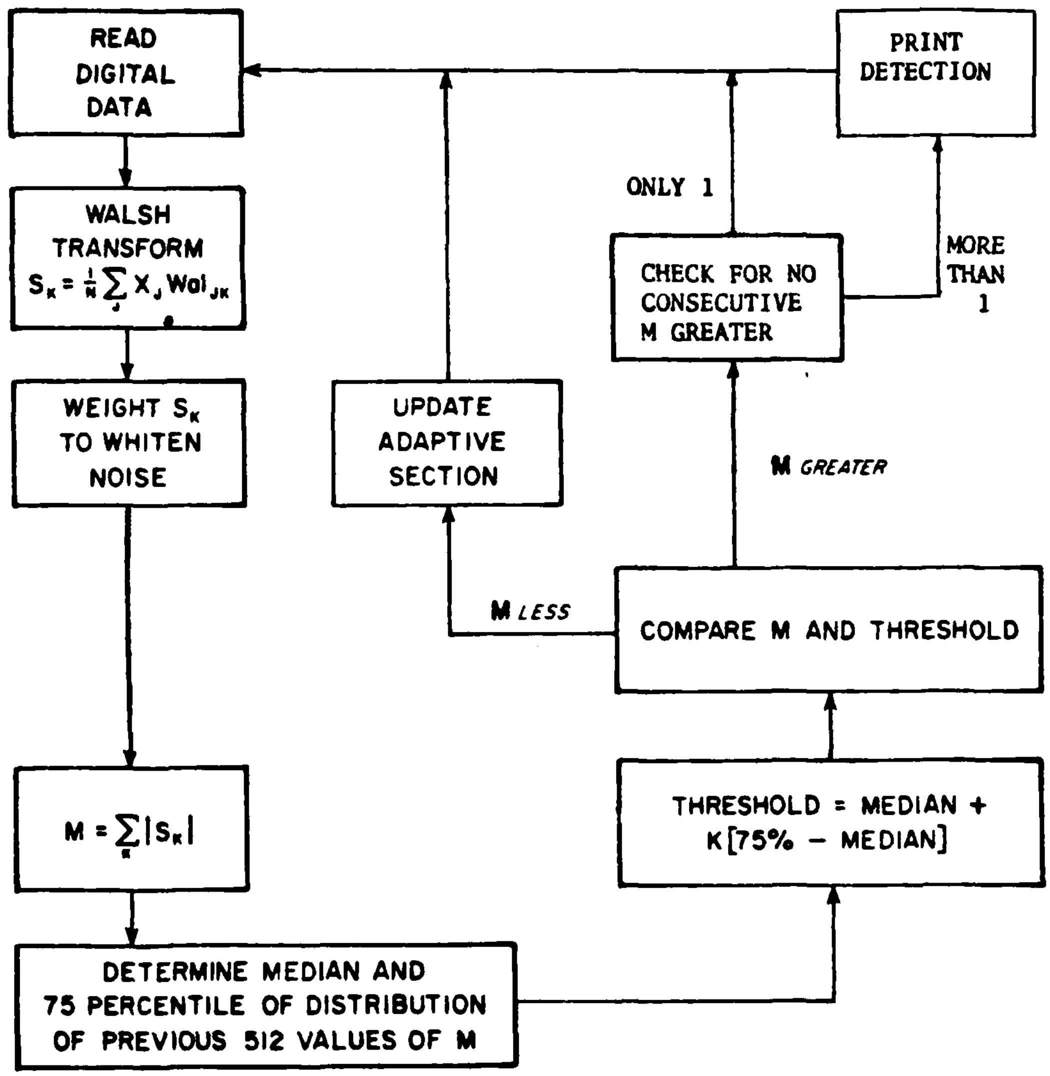

Figure 2. Walsh detection algorithm

$$\text{Threshold} = V_{50} + K (V_{75} - V_{50})$$

where V_{50} = median of the distribution of previous 512 values

V_{75} = 75 percentile of the distribution of previous 512 values

K = arbitrary constant set by operator

If two consecutive values of the sum of the absolute values of the Walsh coefficients exceed the threshold a signal is called. If the current values do not exceed the threshold, they are ranked among the previous 512 values, the oldest value being discarded. In this way an adaptive detection threshold is maintained, the adaptation window being approximately 14 minutes. If a signal is called, the threshold is not updated.

1.2 OFF-LINE DETECTION STUDIES

Indications of the detection capability and false alarm rate to be expected from the application of the algorithm to short-period seismic data were obtained by Goforth and Herrin (1980). Of particular interest were their preliminary results on data recorded at NORSAR. The FORTRAN version of the algorithm was adapted to read NORSAR sub-array tapes for 18 August 1979, and the algorithm was run on the first five hours of the data recorded by the center element of the 02B sub-array. During this period, eight P-waves were detected by the entire NORSAR complement of beams and were associated with specific earthquakes. The algorithm, operating on a single channel, detected seven of the eight and had a false alarm rate of 0.6/hr. The results are shown in table 1.

In a second test using NORSAR data, the algorithm operated on a 7-hour period in which ten P-waves were detected by the array beams and were associated with earthquake occurrences. The algorithm, again operating on the center element of the 02B sub-array, detected 9 of the 10 and had a false alarm rate of 0.9/hour. Although these tests were too limited in extent to draw final conclusions about the detection capability of the technique, the results were extremely promising and indicated that reliable low-level signal detection might be achieved by an inexpensive microprocessor-based system. Geotech, therefore, issued a subcontract to the Geophysics Laboratory of SMU to configure a small microprocessor-based computer system and to implement the Goforth-Herrin algorithm. SMU was also tasked to develop operational parameters for the system which would be suitable for operation at NORSAR and to test the completed system prior to its shipment to Norway. The objectives of the subcontract, as well as the installation of the system at NORSAR, were accomplished during the present reporting period.

Table 1. Earthquakes detected and located by the Norwegian Seismic Array (NORSAR) during the 5-hour period 1979-231-09-50 to 1979-231-15-00.

Region	Magnitude (m_b)	AMP (mu)	Distance (km)	Walsh Detection
Southwestern Kashmir	3.8	1.0	5555	Yes
Taiwan	4.2	1.9	8888	Yes
Central Alaska	3.6	0.5	6222	No
Crete	3.7	1.0	3000	Yes
Northern Celebes	5.9	7.0	11110	Yes
Honshu	3.8	0.8	8333	Yes
Iran	4.2	2.7	4333	Yes
Iran	3.8	1.3	4333	Yes

2. CONFIGURATION OF THE DETECTION SYSTEM

A comprehensive analysis was made of the computer requirements necessary to implement the Goforth-Herrin algorithm for multi-channel operation. On the basis of requirements of core storage, execution speed, precision (word length), and low cost, the North Star Horizon computer was selected as the basic unit of the detection system.

The Horizon computer is a complete microcomputer system with integrated floppy disk memory. It has a Z80A processor board which operates at 4 mHz and has its own programming language with 8 digits of precision. The 8-bit word-length, while adequate, made programming the algorithm considerably more difficult than it would have been had a larger dynamic range been available. The Horizon mother board has slots for up to twelve S-100 circuit boards. Three of the slots are used for the Z80A processor board, a 32K RAM board, and a disk controller board. We also utilize slots for a 16K RAM board and a clock interface. A multiplexer (MUX) and 12-bit analog-digital converter (ADC) board were added to the S-100 bus in order to accommodate multi-channel analog data. The ADC can digitize up to 16 channels simultaneously and has a range of ±10 volts. The MUX-ADC board also contains a programmable binary gain amplifier (PGA) which provides the capability to automatically adjust the voltage level of the noise background. A Geotech TG-120 timing system provides a real-time clock and a 20 Hz signal to key the ADC. The timing information is supplied to the Horizon via a custom-designed interface board which plugs into the S-100 bus.

Control and output of the detection system are provided by the Horizon CRT/keyboard and dual floppy disks and by a Texas Instruments OMNI 800 Printer. A Helicorder is used to provide a visual record of the incoming data.

Analog bandpass filters with corner frequencies at 1 and 8 Hz were incorporated into the detection system for its NORSAR application. The purpose of the filtering is twofold. First, it is advantageous to reduce the size of the 6-second microseisms prior to detection analysis. Filtering can be accomplished in the Walsh domain, but the pre-whitening weights are much more stable in time if the microseisms are removed prior to analysis. Also, the dynamic range of the 8-bit Horizon is not sufficient to accommodate domination of the data by frequencies outside the detection passband. The 8 Hz low-pass section was required to remove the 10 Hz steps introduced by NORSAR's digital to analog conversion of 10 sps digital data.

The filters, multiplexer, PGA, and ADC are packaged with the microprocessor in a 50.8 cm x 20.3 cm x 48.3 cm case. A block diagram of the detection system is shown in figure 3.

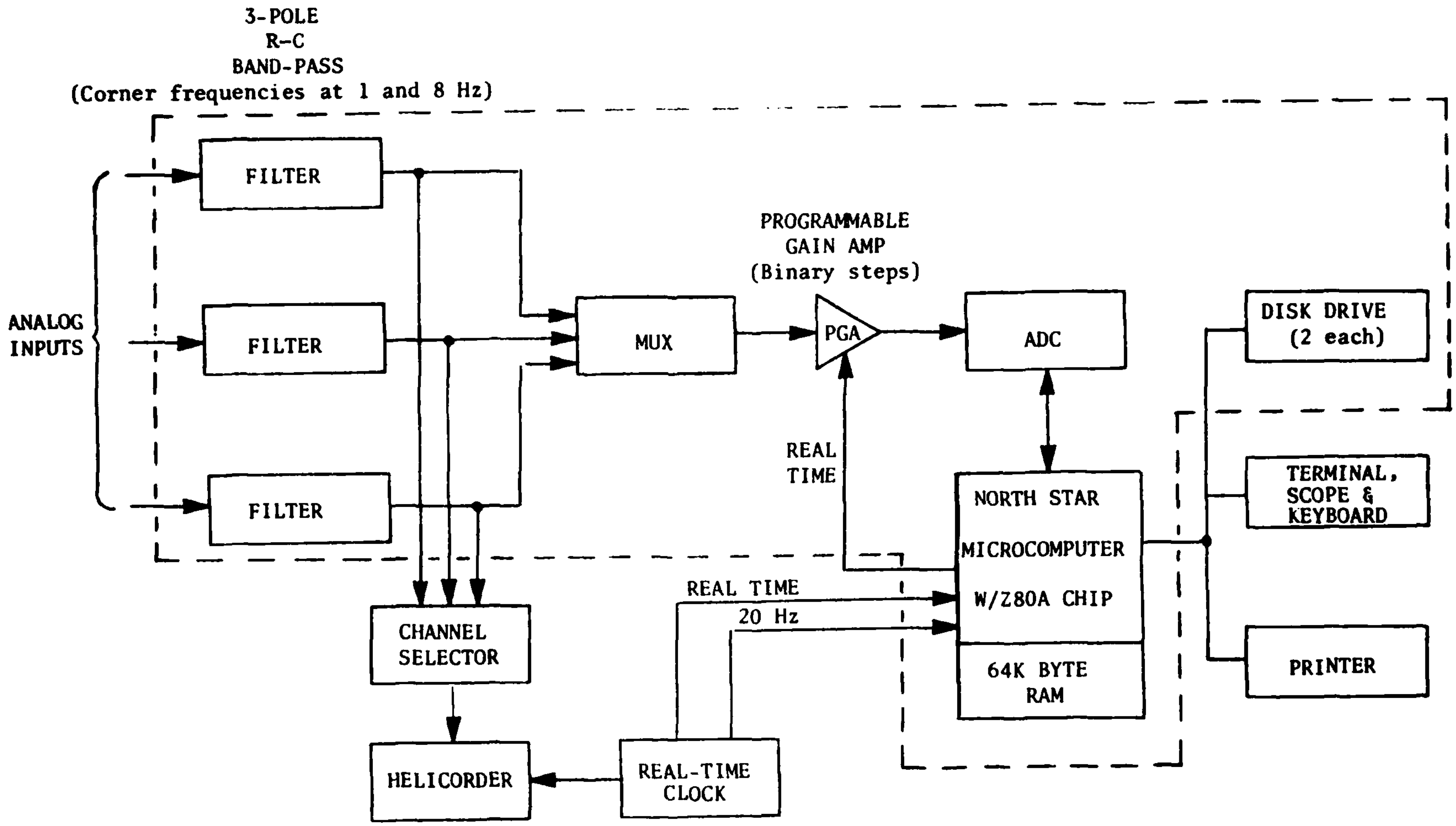

Figure 3. System used at NORSAR to test Walsh signal detector

3. DETERMINATION OF OPERATIONAL PARAMETERS AND TESTING

The Walsh detection algorithm is characterized by various parameters which can be optimized for a particular seismic noise background. These parameters are (1) pre-whitening weights, (2) K, which controls the false alarm rate, and (3) the expected sequency passband of signals.

To obtain the proper pre-whitening weights for NORSAR seismic background, we used NORSAR digital data for the period August 18-26, 1979. Using the central element of the 02B sub-array for 14-minute periods in which no signals occurred, the Walsh spectra of 512 intervals (3.2 seconds/interval) were averaged. The result is shown in figure 4(a). Weights varying from 1 to 1/8 in multiples of 1/8 were determined for each of the 64 Walsh orders. The weights, for the sequency band of interest, are given in table 2. The multiplication of the long-term Walsh noise spectrum by the weights produces the whitened spectrum shown in figure 4(b).

The parameter K determines the level of the detection threshold and is nearly independent of the noise spectrum. Empirical results using noise data from Dallas, Albuquerque, and NORSAR indicate that a K of 4.5 will result in a false alarm rate of the order of 1/hour for a single channel regardless of the type or level of the noise.

The Walsh spectra of several different types of signals recorded at NORSAR were observed to have peak amplitudes in the order band of 8 to 25. This range corresponds approximately to a frequency band of 1 to 4 Hz.

On the basis of these empirical results, the detection parameters to be used initially at NORSAR were selected to be k = 4.5 and the signal band to be Walsh orders 8 to 25. The pre-whitening weights shown in table 2 were chosen for use during the summer operational period.

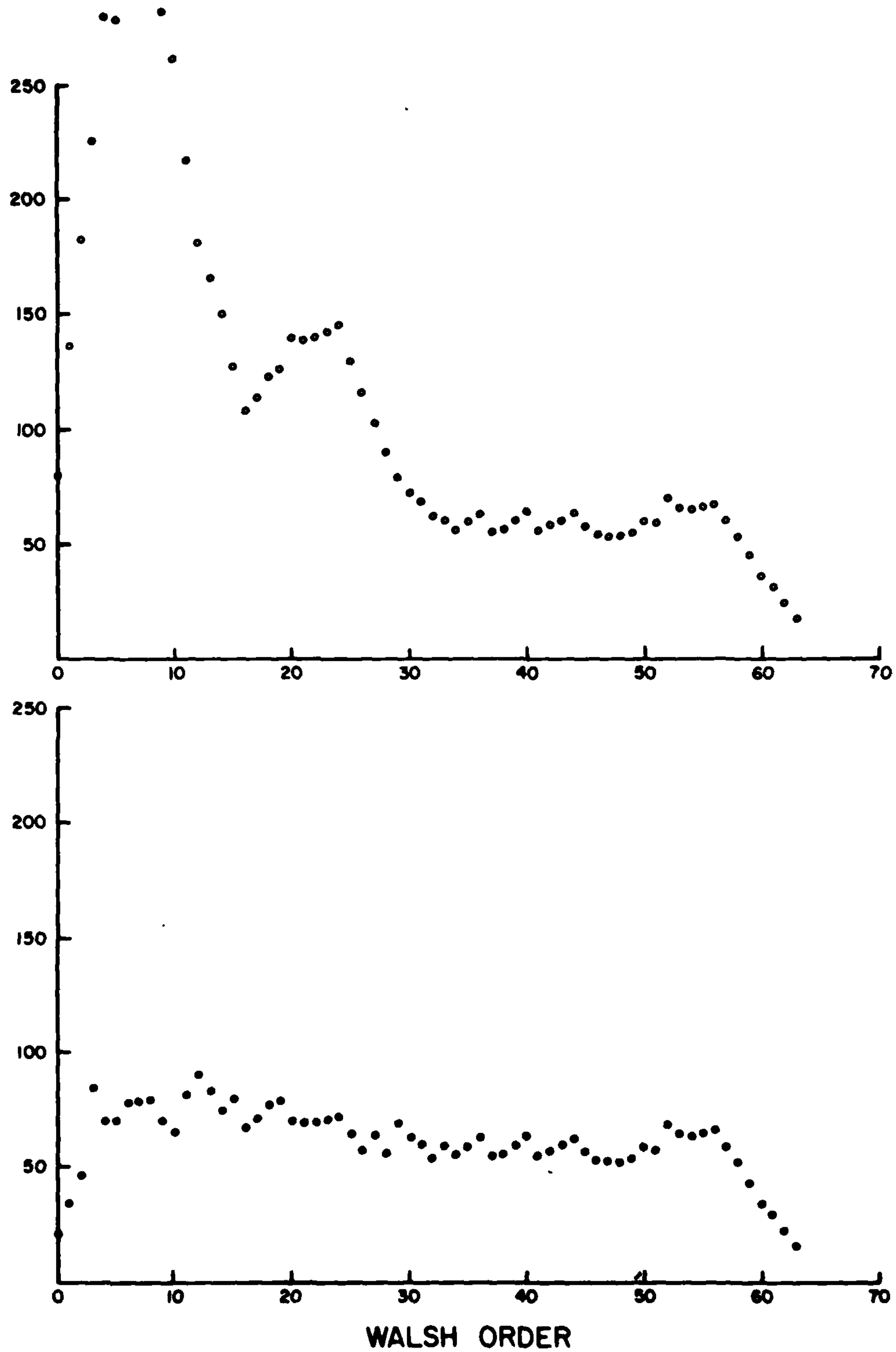

Figure 4. (a) Long-term Walsh amplitude spectrum for NORSAR noise background;
(b) Whitened Walsh spectrum.

Walsh Order	Weight
8	1/4
9	1/4
10	1/4
11	3/8
12	3/8
13	1/2
14	1/2
15	5/8
16	5/8
17	5/8
18	1/2
19	1/2
20	1/2
21	1/2
22	1/2
23	1/2
24	1/2
25	1/2

Table 2. Weights used to pre-whitenen the long-term noise background at NORSAR

4. INSTALLATION OF THE DETECTION SYSTEM AT NORSAR

The basic evaluation of the detector is to be accomplished on-line at NORSAR. The NORSAR array was selected for use in the evaluation because the detector performance on individual channels can be conveniently compared with the performance of the overall array. NORSAR produces detection logs and preliminary event bulletins which will enable us to make rapid evaluations.

Since the Walsh detector was designed to accept data in analog form, it was necessary to determine the most economical way to obtain analog data from NORSAR's digital data stream. After telephone conversations with NORSAR personnel it was decided to utilize three of the eight analog outputs, produced from 10 sps digital data, which are available at the NORSAR data center in Kjeller, Norway. These outputs are normally used by NORSAR personnel to make Brush strip chart records of any eight NORSAR data channels.

Final assembly and testing of the detection system was completed early in June, and on June 18 the system was shipped to Norway. Karl Veith of Geotech met the shipment in Oslo and transported the equipment to the data center in Kjeller. Dave MacKenzie of Geotech and Tom Goforth and Nancy Cunningham of SMU arrived on July 5 to begin installation and checkout.

The entire detection system consisting of the microprocessor, terminal, printer, and Helicorder were situated on two 1 x 2 meter tables adjacent to the Brush digital-analog terminal. During the course of the installation and check-out of the system, we observed that NORSAR has some difficulties in data processing which result in the data flow from some sub-arrays being interrupted more often than others. Their technicians recommended the use of sub-array 03C because of its relatively high reliability. We accepted this recommendation. The 03C sub-array is about average in detection performance and should yield the desired comparison between an "average" sub-array element detection by the Walsh system and a NORSAR beam detection. The location of the 03C sub-array relative to the other sub-arrays is shown in figure 5; the shaded sub-arrays are those currently in operation. Figure 6 shows the locations of the three short-period seismographs in the 03C sub-array which were selected to provide the 3-channel input to the detection system.

NORSAR is in the process of replacing the computer in their Detection Processor system. During the changeover, the Detection Processor has undiagnosed problems which cause it to fail on the average of 4 to 6 times per day. This failure terminates the data flow into our system. When the data flow resumes, the Walsh detector alarms continuously. We, therefore, reprogrammed the microprocessor to shut itself down when the data flow stops. Because of the difficulties involved in programming in Z80A assembly code, no attempt was made at this time to implement an automatic restart when the data flow resumes. At the present time the Walsh detection system is restarted by the same technician who restarts the NORSAR event Detection Processor. The restart process takes approximately 30 seconds.

During the check-out process, it was discovered that program-controlled interrupt requests for data were coming too fast for the ADC module. Idle loops were programmed to allow the ADC to settle between sampling interrupts.

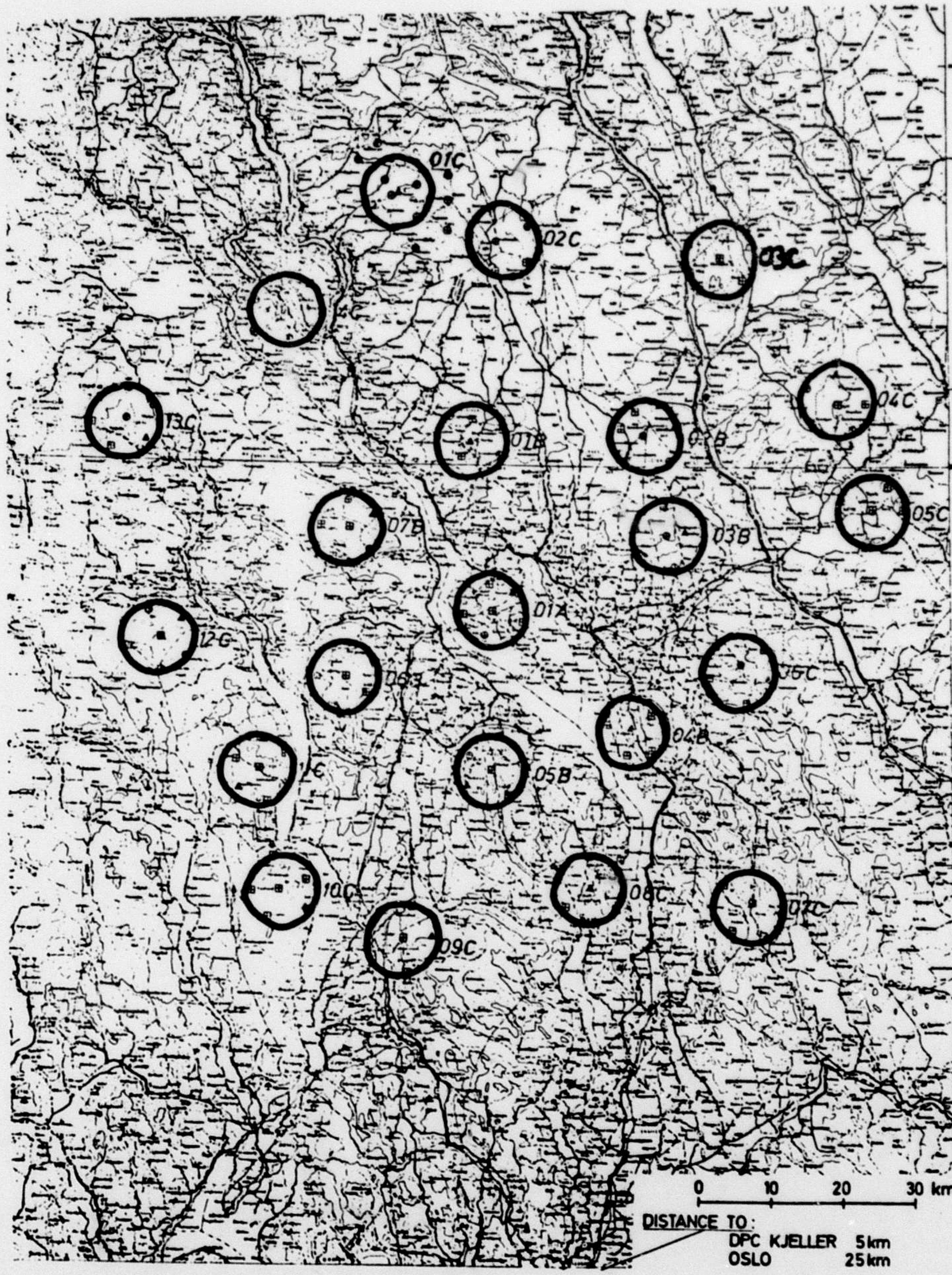

Figure 5. NORSAR array showing position of 03C sub-array.

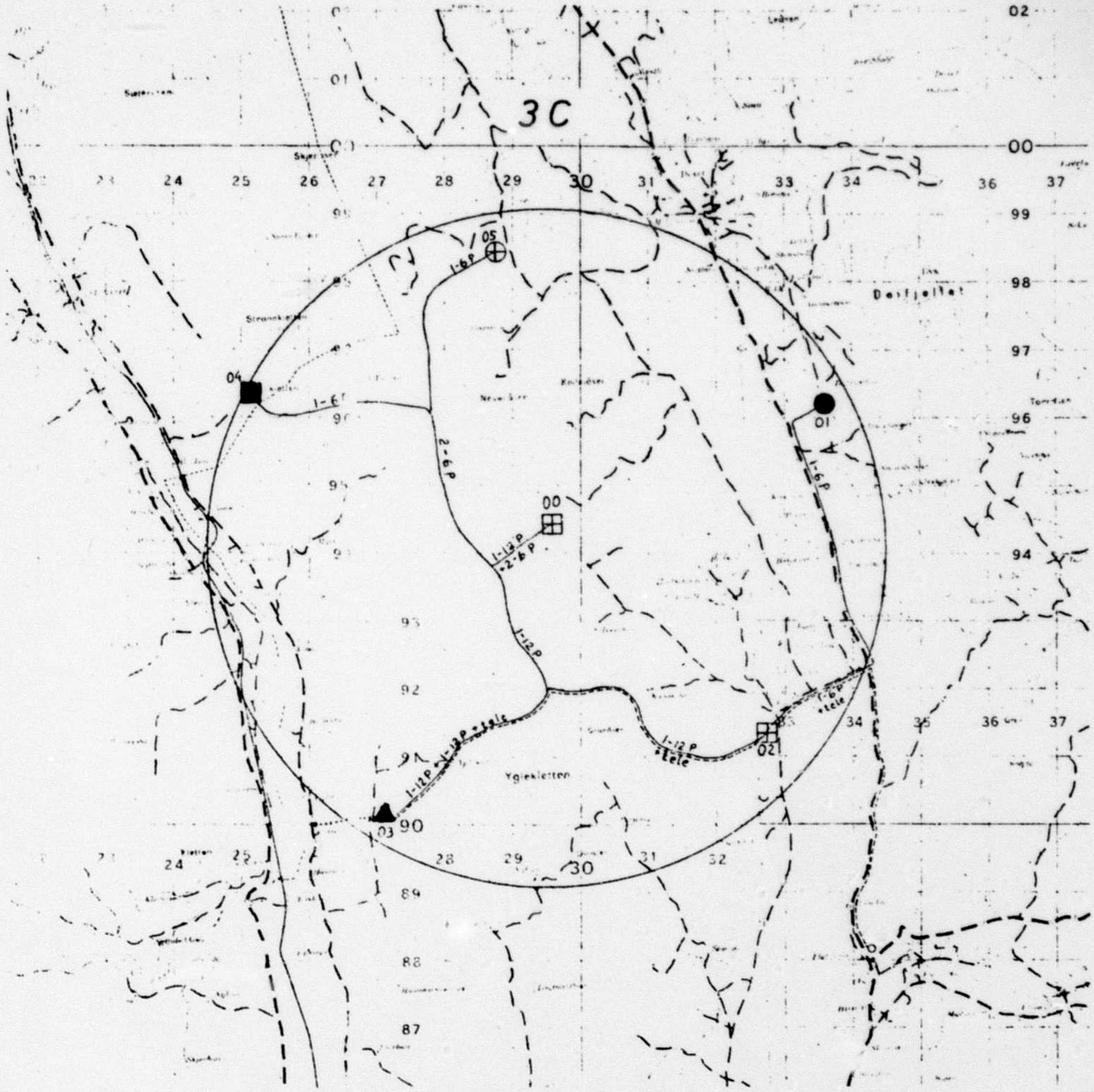

Figure 6. The positions of the short-period vertical seismographs in the 03C sub-array whose outputs were used in the Walsh detection experiment.

A few days after the start up of the system the multiplexer on the ADC unit began to fail. The failure left the system able to process only two data channels. A new ADC module was ordered from California, but it has not been received.

The installation team remained at NORSAR through July 11. Operation of the system on channels 01 and 03 of the 03C sub-array has been satisfactory, but until a new ADC arrives no analysis of channel 04 can be made.

NORSAR personnel were very helpful in interfacing the detection system with the data center equipment, and two technicians have been familiarized with the Walsh system. The NORSAR technicians will routinely change the printer paper and Helicorder records and will maintain clock synchronization. They will also restart the detection program when the NORSAR data stream is resumed after an outage and will perform system maintenance and repair as required.

Preliminary detection results from the first 18 days of operation show the following.

Common Detections	NORSAR only	Walsh only	NORSAR FAR	Walsh only
215	100	53	0.64/hr	0.17/hr (2-ch) 5.0 /hr (1-ch)

False alarms were determined by comparing the detection times with visual analysis of the Helicorder records and of the plots of the NORSAR beam detections which are routinely produced at the NORSAR data center. The above figures show the NORSAR beam system to have about four times the false alarm rate (FAR) of the Walsh system with a two-channel vote. Analysis of the data suggests that NORSAR's detection threshold is about 0.2 magnitude units below that of the Walsh detector. When the new ADC is installed, and 3-channel analysis is possible, we will increase the FAR for the Walsh system to yield about 1 false alarm per hour on a 3-channel vote to see if the Walsh detection threshold can surpass that of NORSAR.

5. REFERENCES

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Walsh, J. L., 1923, A Closed Set of Orthogonal Functions, Amer. J. Math., v. 45, pp. 5-24.

APPENDIX II

TECHNICAL REPORT NO. 81-8

SEMI-ANNUAL REPORT FOR THE PERIOD
15 August 1980 through 15 February 1981

TECHNICAL REPORT NO. 81-8

SEMI-ANNUAL REPORT FOR THE PERIOD
15 August 1980 through 15 February 1981

PROGRAM TITLE

SEISMIC SIGNAL DETECTION ALGORITHMS

Sponsored by

Defense Advanced Research Projects Agency
ARPA Order No. 3291-32
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Program Code	0D60
Name of Contractor	Teledyne Geotech
Effective Date of Contract	1 December 1979
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Amount of Contract Dollars	$198,113
Principal Investigator	K. F. Veith
Program Manager	K. F. Veith
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SEMI-ANNUAL REPORT FOR THE PERIOD
15 August 1980 through 15 February 1981

SEISMIC SIGNAL DETECTION ALGORITHMS

1. INTRODUCTION

This report covers progress made during the period 15 August 1980 through 15 February 1981, on a contract to implement and test an automatic event detection algorithm that is based on the Walsh transform. The objective of the program is to develop a microprocessor system with event detection capabilities and false alarm rates comparable to those now being achieved in large computer systems.

During the previous reporting period the Goforth-Herrin detection algorithm was successfully implemented and tested on a Z80A-based microcomputer, and the system was placed in operation at the Norwegian Seismic Array (NORSAR) for on-line evaluation. The detection system has been in operation at NORSAR during the 6-month interval of the present reporting period, and an evaluation of the system operation and effectiveness is presented in this report. Also included is a report of the performance of the detection algorithm in off-line tests utilizing standard tapes prepared by Teledyne Alexandria Laboratories (under AFTAC/VSC supervision).

2. NORSAR DETECTION EXPERIMENT

The purpose of installing the Walsh detection system at NORSAR was tc provide on-line operational experience in a situation in which the Walsh results could be easily compared to a standard. Since NORSAR provides on-line detection on 322 beams and produces detection logs and preliminary event bulletins, a high-quality standard is readily available. Although the microprocessor-based Walsh system is capable of analyzing up to 10 channels of 20 sps data, only 3 channels were analyzed during the NORSAR experiment. Figure 1 shows the 03C sub-array which is located in the northeastern edge of the NORSAR array. The location designated 01, 03, and 04 were selected to provide the input to the detection system. Sub-array 03C is the most reliable of the sub-arrays in terms of outage time, and it is intermediate in terms of detection capability. Sites 01, 03 and 04 form a triangle with sides 6 to 8 km long, a sufficient separation to assure incoherence of the short-period noise background but not so great as to produce significant "step-out" across the array for teleseismic P-waves. Detection analysis was performed independently on the 3 channels, with a detection being called if all channels raised a flag during the same 3.2 sec analysis window. The details of the single-channel Walsh algorithm are given in the previous semi-annual technical report.

The standard to which the Walsh system was compared is the NORSAR Detection Processor, in which the event detection procedure consists essentially of a continual signal-to-noise ratio test on each of 322 real time array beams which have been bandpass filtered for additional noise suppression. Whenever a short-term average (STA) exceeds a long-term average (LTA) by a factor of 3 on a beam a certain number of consecutive times, a detection is delared on that beam. A computer plot is made of the segment of the beam seismogram in which the signal is called. These plots were useful in determining whether a NORSAR Detection Processor detection was a valid seismic signal or a false alarm. Later phase and side-lobe detections on the beams were not called false alarms in spite of the resulting erroneous estimate of the source regions.

A continuous Helicorder record was made of 03C-01 input to the Walsh detection system. False alarms and detections on the Walsh system were determined by visual analysis of the Helicorder records.

The analog-digital converter (ADC) in the Horizon microcomputer partially failed a few days after the system was installed. As a result, the Walsh detector was forced to operate on only two channels from 11 July to 10 September 1980 (instead of the intended 3 channels), and detections were determined by a 2 out of 2 channel vote. However, compared to 1-channel detection, the 2-channel vote enabled the detection threshold of the individual channels to be lowered by reducing K from 4.5 to 3.0. Numerous data outages occurred due to malfunctions in the NORSAR Detection Processor so that only 625 hours of data were available during this period for comparison of the Walsh and NORSAR detectors. The detection results are summarized in Table 1.

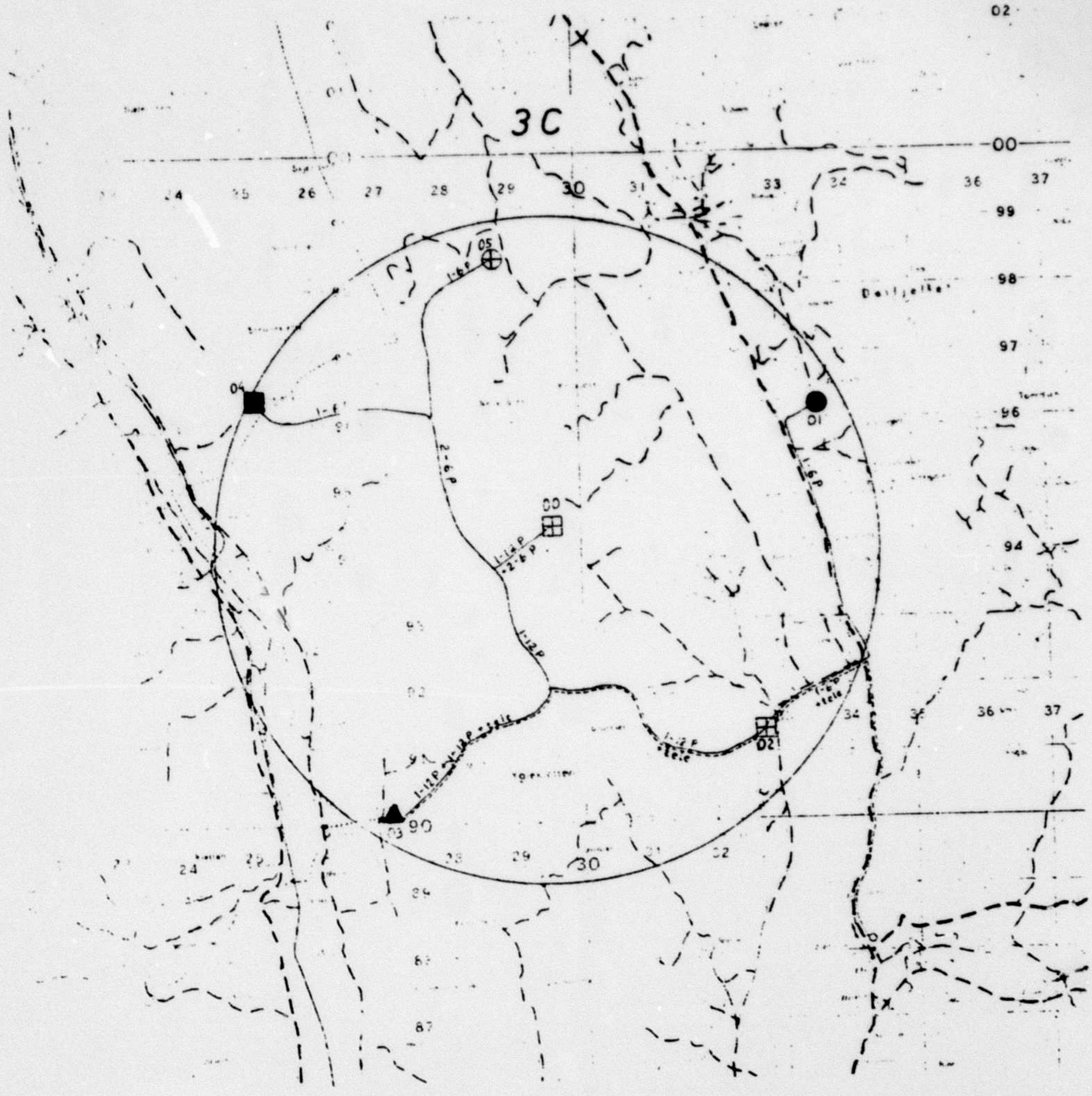


Figure 1. The positions of the short-period vertical seismographs in the 03C sub-array whose outputs were used in the Walsh detection experiment.

Table 1. Comparison of NORSAR Detection Processor and Walsh 2-channel vote during the period 11 July - 10 September 1980

Events Detected by both	Events Detected by NORSAR only	Events Detected by Walsh only	NORSAR False Alarm Rate	Walsh False Alarm Rate
337	146	80	0.67/hr	0.16/hr

A visual examination of the 146 events detected only by NORSAR indicates about the same mix of locals, regionals, and teleseisms as does an inspection of the 80 events detected only by the Walsh system, and we can consider the two groups of events to be from the same population. Therefore, in this period NORSAR detected a total of 483 events with a false alarm rate (FAR) of 0.67/hour, while the Walsh system detected 417 events with a false alarm rate of 0.16/hour. If the total number of events is assumed to follow a log N = A-1.0 m_b distribution, then the NORSAR beams show a detection threshold 0.06 magnitude units lower than the 2-channel Walsh system, but with four times the false alarm rate.

On September 10, 1980, a delay line chip failed in the North Star Horizon computer, and the detection system was shut down. Additional problems and maintenance requirements had accumulated during the two months of operation. In particular, the analog-digital converter (ADC) chip, after six weeks in transit, had finally arrived at NORSAR and needed to be installed. The original chip had partially failed a few days after installation of the system, and as noted previously only two data channels could be analyzed. Also, we had found that the Helicorder records were not ideal. The 24-hour records required a gain that was too low to resolve the character of many of the low-level signals. Another inconvenient aspect of the operation was that the Walsh system printed detections on both channels, and an analyst was required to make an off-line manual vote. While providing some useful information initially, it proved not to be worth the additional analysis time. Another consideration was the possible change in the Walsh noise spectra with the onset of the Norwegian winter.

In order to address these problems, a geophysicist and a programmer were returned to NORSAR and remained during the week 11-19 October 1980. The following resolutions were obtained:

1. The new ADC and delay line chips were installed. An additional problem was discovered in the disk controller board; it was also replaced and the faulty board was returned for repair.

2. A second recording unit (an MEQ-800) was obtained from the NORSAR inventory and interfaced with the Walsh system timing control. This allowed each record to cover only eight hours, and the gains could be run sufficiently high to permit better resolution of low-level events.

3. The Walsh algorithm was reprogrammed to take an internal vote among the three data channels. In addition, logic was added to put the Walsh coefficient sum for a single-channel detection flag into the noise background array for that channel if the subsequent 3-channel vote was not unanimous, i.e., no signal was called. This prevented the low thresholds used with voting from generating positive feedback in the system with resulting instability. This change, along with the internal 3-channel vote made possible by the new ADC chip, allowed the Walsh detector to routinely search for signals among about 10% of the noise distribution for a single channel without overloading the system with excessive false alarms.

4. Numerous Walsh spectra of the background noise were obtained from each of the three individual channels of data to be analyzed. The spectral shape was quite consistent among the channels, but it had changed somewhat with the onset of high 6-second microseisms. The equivalent frequency range used for detection in the Walsh system is approximately 1.25 Hz to 3.76 Hz. The Walsh noise spectra obtained in October indicated a 6 dB rise in amplitude in the lower frequency end of the passband as compared to the July results. This suggests that the seasonal dependency of the background noise at NORSAR will require seasonal adjustments of the pre-whitening weights. The pre-whitening weights were changed to accommodate the new spectral shape. The overall level of the channels varied somewhat due to differences in system gains. The 03 element of the 03C sub-array had the lowest noise level, while the 04 and 01 elements were 2 and 4 dB higher, respectively.

With all three channels operational and an internal unanimous vote required for a detection, it was possible to lower the detection threshold of the individual channels to K = 2. In this mode the Walsh detection system operated on channels 01, 03 and 04 of the 03C sub-array from 18 October 1980 through 4 January 1981. During this period 1174 hours of data were available for comparison with the NORSAR beams. The primary problems limiting the data availability were repeated malfunctions of the NORSAR Detection Processor. The analysis results for this period are shown in Table 2.

Table 2. Comparison of NORSAR Detection Processor and Walsh 3-channel vote during the period 18 October 1980 - 4 January 1981

Events Detected by both	Events Detected by NORSAR only	Events Detected by Walsh only	NORSAR False Alarm Rate	Walsh False Alarm Rate
879	162	468	0.70/hr	0.21/hr

Table 2 indicates that NORSAR detected a total of 1041 events with a false alarm rate of 0.70/hr, while the Walsh system detected 1347 events with a false alarm rate of 0.21/hr. This gives a lower detection threshold for the Walsh system by 0.1 magnitude unit. A cursory visual inspection of the detections which failed to trigger both systems indicates that they are mostly locals and regionals, and the lower detection threshold of the

Walsh system is undoubtedly due to the general insensitivity of the NORSAR beams to these events. The increased detection capability shown by the Walsh 3-channel vote as compared to the 2-channel vote was accompanied by a slight increase in the false alarm rate from 0.16/hr to 0.21/hour.

We conclude from the 6-month experiment at NORSAR that the microprocessor-based Walsh detection system, operating on three individual channels, is comparable in detection capability to the NORSAR Detection Processor operating on 322 beams, while running at a FAR of about one-third that of the Detection Processor. It is, of course, realized that NORSAR does not use local and regional beams and that many of their missed signals are in this category. If the signal population were limited to teleseisms, NORSAR's detection threshold would probably be lowered relative to that of the Walsh system, but such a comparison cannot be made without confirming the locations of all the events detected by the two systems.

Two additional factors should be considered in interpreting the results. First, the Detection Processor false alarm rate may be somewhat overestimated. In some cases, beam plots were not available to us, and NORSAR false alarms were called on the basis of no visible energy on the Helicorder recordings of 01-03C, 03-3C, or 04-03C. Assuming that the Detection Processor analysis of beams has a lower detection threshold than does visual analysis of individual channels, some valid signals may have been classed as false alarms. Second, the detection capability of the Walsh system may be slightly underestimated. The algorithm voting logic required all three channels to trigger within the same transform window (3.2 sec) in order to get a positive vote. Since waveforms require a finite time to traverse the 6 to 8 km spacing between the array elements, and because this time is greater for local and regional signals, there is a slight probability of the vote rejecting a valid signal, particularly for the near events.

3. WALSH ANALYSIS OF STANDARD TAPES

Pursuant to instructions from Mr. William Best and Col. George Bulin, an evaluation of the Walsh detection algorithm was made on the DEC VAX 11/780 using the standard test tapes furnished by SDAC.

3.1 TEST DATA

Two test tapes were evaluated. The first contained 22 hours, 40 minutes, of NORSAR data sampled at 10 sps. The second contained 20 hours, 40 minutes, of Pinedale data sampled at 20 sps. The noise data from both stations were phase scrambled and test signals were buried in it every nine minutes at signal-to-noise (S/N) ratios of 1/2, 1/4, 1/8, and 1/16. Thirty-four different signals were put in the NORSAR noise at each of the S/N values and thirty-one signals in the Pinedale data. Because of the limited time frame for this analysis, no attempt was made to optimize the detection capability of the Walsh algorithm. Th͜ system had been operating on 1-4 Hz data, so the tapes were put through simple 3-pole, high-pass recursive filters. These used:

$$Y_n = \sum_{i=1}^{4} a_i X_{n+4-i} - \sum_{j=1}^{4} b_j Y_{n-j}$$

where Y_n is the nth filtered data point

X_n is the nth unfiltered data point, and

a_i, b_j are the filter coefficients

For NORSAR, a corner frequency of 1 Hz was selected. This gave coefficients of (for 10 sps)

a_1 = 0.52762449

a_2 = -1.5828733

a_3 = 1.5828733

a_4 = -0.52762449

b_1 = -1.7600427

b_2 = 1.1828935

b_3 = -0.27805996

For Pinedale, a corner frequency of 0.75 Hz was used. This gave

$$a_1 = 0.78964579$$
$$a_2 = -2.3689375$$
$$a_3 = 2.3689375$$
$$a_4 = -0.78964579$$
$$b_1 = -2.5298080$$
$$b_2 = 2.1638198$$
$$b_3 = -0.62353861$$

These filters proved to be extremely fast, taking only 1.5 and 3 minutes of CPU time to process the entire data tapes from NORSAR and Pinedale, respectively. This high speed strongly suggests that similar filters could be programmed into the Walsh system in the microcomputers and the analog filters could be eliminated from the system. In this configuration, the Walsh system could handle the direct digital input from the remote NORSAR stations without converting first to analog.

A general look at the noise background after filtering revealed several interesting features.

a. At NORSAR, the background noise level as averaged over 9 minute segments steadily decreased from the start through the first 14 hours and 20 minutes. Total decrease in the level was about 15 percent. It then suddenly increased by a factor of nearly 35% (as measured from average Walsh coefficients) and continued to decrease to near its original level.

b. Pinedale background noise fluctuations showed somewhat similar trends, but the excursions from the overall average levels were only about ±7 percent. This was less than half the background variation of NORSAR.

c. At 12 hours and 10 minutes NORSAR had a period of about 40 minutes where the high frequency noise levels doubled.

d. The Pinedale data had several spikes in it.

3.2 DETECTION ANALYSIS

Each data set was processed with several FAR's in order to establish the relationship between FAR and number of events detected. Because the events on the tape could start up to 10 seconds early and the signals persist up to 30 seconds after start, detections were declared if the system called an event anywhere from -10 to +30 seconds of the 9 minute mark.

The Walsh detector maintains an ordered array of background noise samples which are the sum of the absolute values of the Walsh coefficients over the sequency range desired for detection. The detection threshold is set to be:

$$T = K\,(S_{75\%} - S_{50\%}) + S_{50\%}$$

where T is the threshold value for a new sum
K is the coefficient which sets the FAR
S is the background sum array (75% and 50% values are used)

The normal Walsh transform window size of 3.2 seconds was used with a 1.6 second overlap in consecutive transforms. A background array size of 512 samples (or 13 minutes, 39.2 seconds) was used. Two consecutive coefficient sums above the threshold was required to declare a detection. The first 9 minutes of each tape was used to establish the weights for whitening the noise in the Walsh domain and those relative weights remained constant throughout the analysis. The 8^{th} to 25^{th} Walsh coefficients were used for NORSAR (1.2 to 3.9 Hz) while the 6 to 13 Walsh coefficients were used for Pinedale (0.9 to 2.0 Hz).

3.3 RESULTS

The analysis results are presented in Table 3 and Figure 2. As Figure 2 shows, there is extremely high consistency between the results for NORSAR and for Pinedale. This reflects the general robust nature of the algorithm. The normal scatter for the two data sets is about ±4% of the average detection percentile while it reaches values of ±9% of the average FAR value. The consistent trends make it extremely easy to define the necessary K value for any selected FAR rate desired for a single channel detector.

The execution speed of the Walsh algorithm is extremely fast. The NORSAR data took 8 minutes and 30 seconds to process while the Pinedale data required 8 minutes and 45 seconds of CPU time. This gives the processing speeds shown below:

	Time for Processing	Processing Rate	Time for Filtering	Total Rate
NORSAR (10 sps)	8:30	160 times real time	1:30	136 times real time
Pinedale	8:45	142 times real time	3:00	106 times real time

Thus, while processing would be slowed down a little by the addition of a recursive filter to the algorithm, the minimum processing rate for 20 sps data still exceeds 100 times real time.

In Figures 3 and 4, the Walsh algorithm results are compared to those of the other investigators. Only the lines from Figure 2 have been included in the figures to avoid confusion with other results. Because the actual detection thresholds achieved by the various algorithms are difficult to define, the comparisons are made in terms of detection percentile achieved with its corresponding FAR. Thus, each detection percentile defines an equivalent K value which then enables the FAR values to be compared. Because of the scatter noted in figure 1, the analysis results from other procedures needed to be outside the ±10% dashed lines to be regarded as significantly

Table 3. Walsh algorithm detection results

NORSAR

S/N	1/2		1/4		1/8		1/16		Total			Detection
K	F	D	F	D	F	D	F	D	F	D	FAR	Percentile
3.3	54	31	42	23	42	14	65	7	203	75	9.0	.551
3.5	30	31	20	18	33	11	33	5	116	65	5.1	.478
3.61	26	30	16	18	32	10	29	3	103	61	4.5	.449
3.7	25	29	13	16	24	10	24	3	86	58	3.8	.426
4.0	14	27	7	15	17	5	14	1	52	48	2.3	.353
4.5	8	26	4	10	6	3	7	1	25	40	1.1	.294

Pinedale

S/N	1/2		1/4		1/8		1/16		Total			Detection
K	F	D	F	D	F	D	F	D	F	D	FAR	Percentile
3.3	38	31	41	17	41	10	50	5	170	63	8.2	.508
3.5	25	31	46	14	24	8	23	4	118	57	5.7	.460
3.7	19	30	32	12	19	7	17	3	87	52	4.2	.419
4.0	11	30	15	8	7	3	10	3	43	44	2.1	.355
4.5	3	28	9	7	4	2	3	2	19	39	0.92	.315

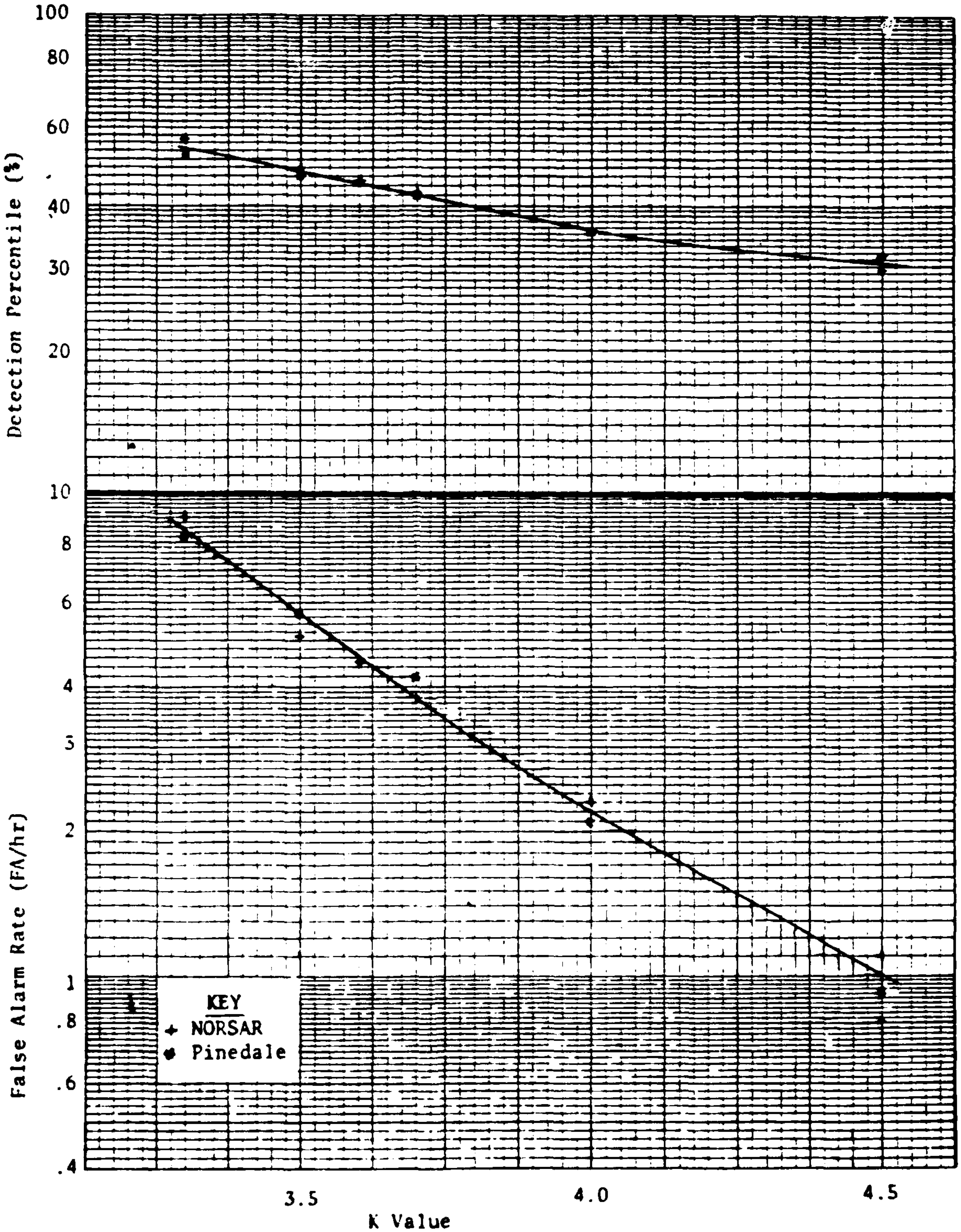


Figure 2. Walsh Algorithm Results on NORSAR and Pinedale Test Tapes.

Figure 3. Comparison of Walsh Algorithm Performance at NORSAR.

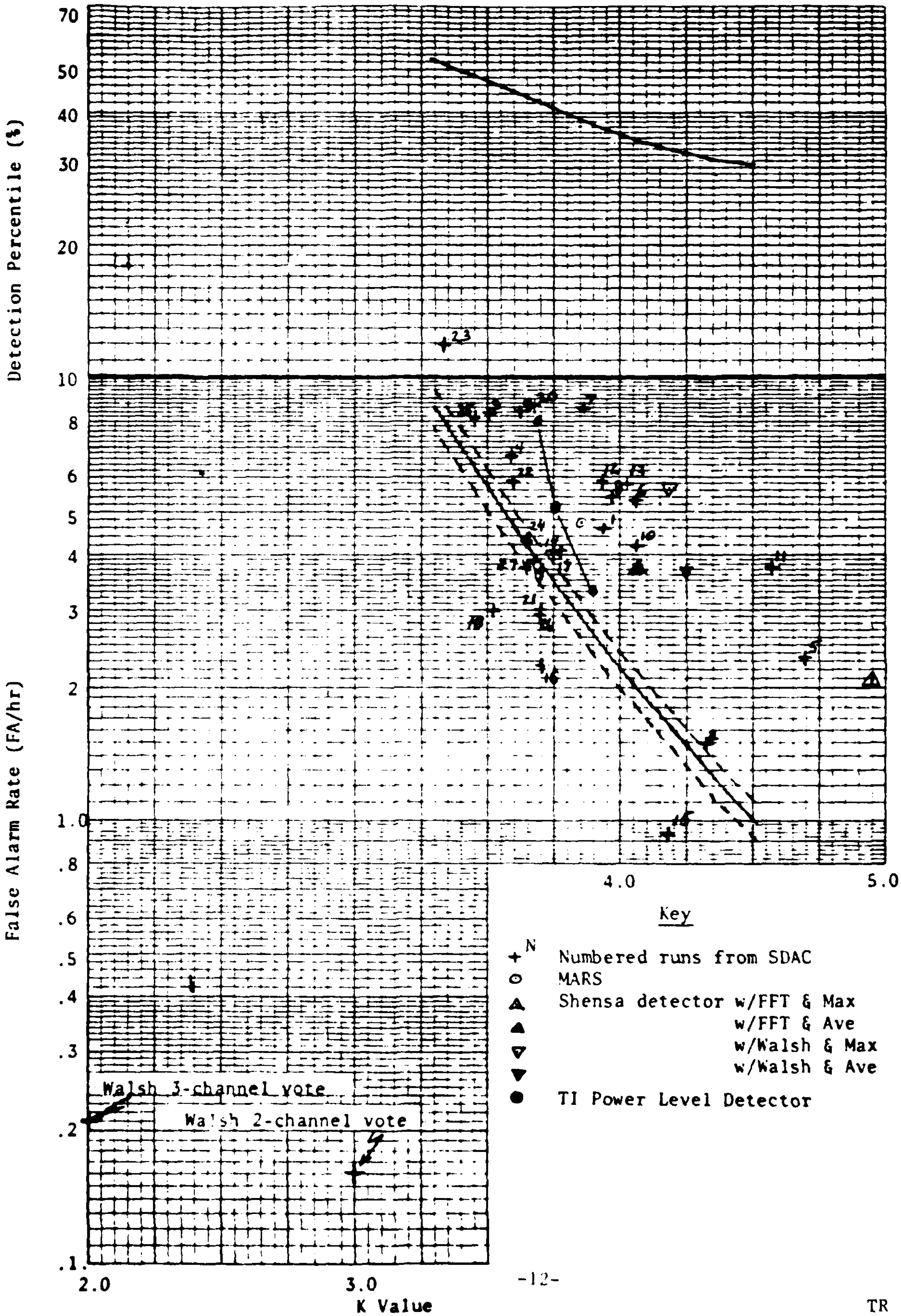
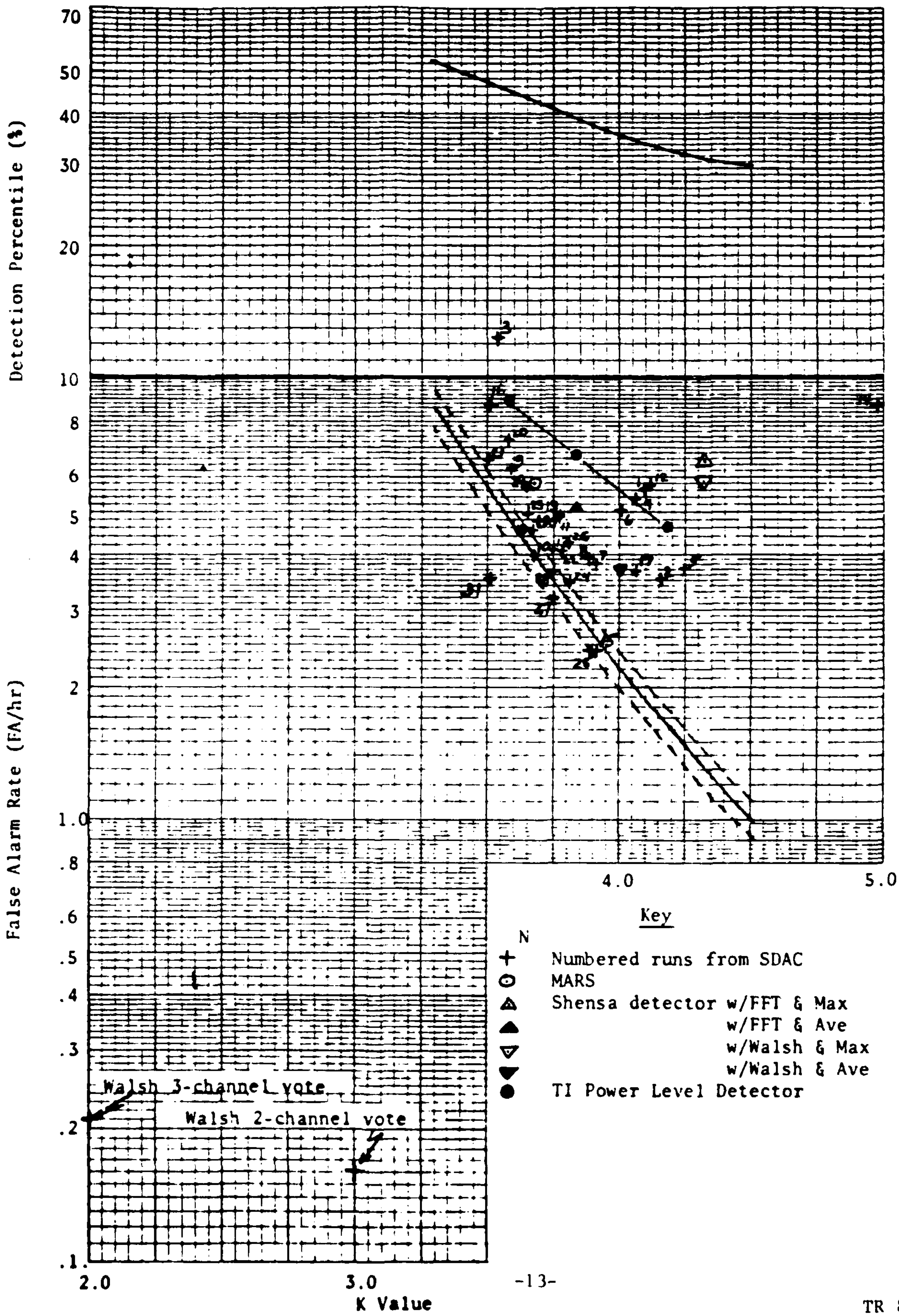


Figure 4. Comparison of Walsh Algorithm Performance at Pinedale.



better or worse then the Walsh algorithm. (Results were taken from Single Channel Event Detection: SDAC-TR-81-7 and Mike Shore's summary of the Seismic Detection Meeting of 2-3 December 1980).

There are several important points to be noted in general. First, neither the MARS, Shensa, nor the TI power level detector approaches the Walsh detector in detection threshold at a FAR within 20% of the FAR for Walsh. Next, while the Walsh algorithm showed great consistency in performance between NORSAR and Pinedale, the other detectors were quite erratic. Comparable runs showed neither the same detection capability nor the same FAR. This characteristic of the Walsh algorithm is believed to be due to the robust nature of the statistic used for detection. It has nothing to do with the properties of the Walsh transform per se as evidenced by the erratic behavior of the Shensa detector when the Walsh transform is utilized instead of the Fourier transform. Finally, while several of the runs made by SDAC exceeded the Walsh performance, it should be emphasized that because of the short time period available for analysis, no attempt was made to optimize the Walsh detector. Initial estimates for the whitening weights, the processing passband, the detection passband, and long-term noise characteristics (background array size) were made and maintained throughout the analysis. Optimization of these factors could make a significant improvement in the Walsh algorithm performance on these test sets.

The results of the SDAC runs relative to the Walsh results are shown below.

Performance

	Better		Comparable		Worse	
	NORSAR	Pinedale	NORSAR	Pinedale	NORSAR	Pinedale
Run Numbers	15	31	19	10	1-14	1- 9
	16		24	15	17	11-14
	18		27	25	20	16-24
	21			27	22-23	26
	26			28	25	29-30
						32
Totals	5	1	3	5	19	26

Because of the varied nature of the SDAC test detectors, please refer to the SDAC report for the exact parameters used on each test run.

For comparison purposes, the FAR's for the Walsh 2- and 3-channel voting detector at NORSAR were included in figures 2 and 3. Extrapolation of the 1-channel FAR curve suggests that the 2-channel vote reduces the FAR to about 1 percent of the single channel level, and to less than 0.2 percent for the 3-channel vote.

3.4 RECOMMENDATIONS

Because of the high detection capability, low FAR and extreme speed of the Walsh seismic event detection algorithm, efforts should be made to determine its optimum mode of operation. This additional study falls into two natural categories. The first is optimization of a single channel system, while the second is optimization of a multi-channel system. For the optimization of a single channel detector, we must understand the true nature of the time variability of the background noise as well as the normal frequency content and onset characteristics of the desired signals as observed in the Walsh domain. These characteristics would enable the optimal size of background array, transform window, and detection passband(s) to be determined. It would also define the need for time variable noise whitening weights, as well as the time frame over which they should adjust. Finally, it would define the characteristic Walsh sequencies for each type of signal and, thus, define the optimal sequency coefficients to use in order to separate the various signal types from the station background noise.

The multi-channel detector has been shown to be significantly better than the single-channel detector, particularly in reducing the FAR value. But as yet the optimal mode of multi-channel utilization is not known and could have significant impact on future array design. For the Walsh vote, the element spacing must be far enough apart to make the noise incoherent while still preserving the energy level of the signal. The 6 to 8 km spacing worked well at NORSAR, but similar results might have been achieved with 1 to 2 km spacing. Data from arrays such as the 13-element station in Alaska should be analyzed to determine:

a. The relationship between voting FAR values and array element spacing.

b. The relationship between the probability of a false alarm and the probability of missing a small event by requiring N out of M elements in the vote.

c. The comparative detection capabilities of a single channel detector operating on an array beam and a multi-channel vote operating on the elements of the array.

APPENDIX III

TECHNICAL REPORT NO. 81-9

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15 February 1981 through 15 August 1981

TECHNICAL REPORT NO. 81-9

SEMI-ANNUAL REPORT FOR THE PERIOD
15 February 1981 through 15 August 1981

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SEISMIC SIGNAL DETECTION ALGORITHMS

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Principal Investigator	K. F. Veith
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1. INTRODUCTION

This report covers progress made during the period 15 February 1981 through 15 August 1981, on a contract to implement and test an automatic event detection algorithm that is based on the Walsh transform. The objective of the program is to develop a microprocessor system with event detection capabilities and false alarm rates comparable to that now being achieved in large computer systems.

During the first year of the program, the Goforth-Herrin algorithm was successfully implemented and tested on a Z80A-based microcomputer, and the system was placed in operation at the Norwegian Seismic Array (NORSAR) for on-line evaluation. The analysis of a 6-month operational period at NORSAR indicated the Walsh system had a detection threshold comparable to the NORSAR Detection Processor while operating at one-third the false alarm rate. An off-line evaluation of the detection algorithm using Geotech's DEC 11/780 computer on standard test tapes furnished by SDAC demonstrated that the Walsh system was one of the better systems tested. During the present reporting period effort was concentrated upon potential modes of optimizing the Walsh algorithm for single channel systems.

2. WALSH ANALYSIS OF SDAC TEST TAPES

As reported previously, two test tapes prepared by Teledyne Alexandria Laboratories for SDAC were analyzed by the Walsh detection process. The first tape contained 22 hours and 40 minutes of single-channel Norwegian Seismic Array (NORSAR) data sampled at 10 samples/second, and the second contained 20 hours and 40 minutes of Pinedale data sampled at 20 samples/second. Test signals were superimposed on the noise every 9 minutes at signal-to-noise ratios of 1/2, 1/4, 1/8, and 1/16. Thirty-four different signals were added to the NORSAR noise at each of the S/N values, and thirty-one were added to the Pinedale noise at each S/N.

The results of the Walsh analysis of these tapes indicated that the Walsh detection algorithm had a significantly lower detection threshold than did the MARS, Shensa, and Texas Instruments detectors operating at the same false alarm rate. No attempt was made during the tests to optimize the operational parameters of the Walsh detector. Initial estimates for the pre-whitening weights, the processing passband, the detection passband, and long-term noise array size were used unchanged throughout the analysis.

2.1 DETERMINATION OF OPTIMUM DETECTION PARAMETERS

The SDAC test tapes were used to optimize the Walsh algorithm for operation on single channel systems. This was accomplished by varying the various operational parameters and comparing the detection results with the results obtained using a "standard" set of parameters. All analysis runs were conducted using pre-filtering by a high-pass digital recursive filter with corner frequencies of 1.0 Hz (NORSAR) and 0.75 Hz (Pinedale).

The standard Walsh performance runs on the two data tapes were made under the following conditions:

Background sample size	- 512 samples or 13 minutes 39.2 seconds
Transform window size	- 3.2 seconds
Window overlap	- 1.6 seconds
Number of consecutive windows above threshold to declare event	- 2 windows (4.8 seconds of signal)
Noise pre-whitening weights	- fixed by initial 14 minutes of noise data
Detection band	- set by "normal" event frequencies observed at the stations NORSAR 1.25 to 3.75 Hz Pinedale 0.94 to 1.88 Hz
Detection threshold	- Varied by setting K value and establishing the detection threshold - False Alarm Rate (FAR) relationship

The results of the standard runs are given in Figure 1. Because the seismic events on the test tapes were in groups of four with fixed signal-to-noise (S/N) ratios of 1/2, 1/4, 1/8 and 1/16, it was possible to express the detection performance in terms of percentile of the total number of events on each tape. This allows direct comparison of the algorithm performance between the two stations. Indeed, the Walsh detector performed with extremely consistent results on the standard runs for both NORSAR and Pinedale.

The effects of variations from the standard of the Walsh detector control parameters were evaluated to determine the optimal mode of operation. Table 1 shows the parameters involved and gives the figure in which the corresponding results are depicted. The figures (2-20) are generated by using the observed detection percentile for each run to obtain the equivalent K value (detection threshold control) of the standard runs and then plotting the observed FAR in relation to the standard. This mode of analysis transfers all of the performance variations into the FAR to allow a quick evaluation of the enhancement or degradation of the detector's performance.

Figures 2 and 3 show the effects of reducing the background array size from 512 samples (<14 minutes) to 256 samples (<7 minutes) and 128 samples (<3½ minutes), respectively. This change merely limits the time frame which is used to judge the normal fluctuations in the noise levels. Figure 2 suggests that the 7 minute background array might give some improvement in performance at the lower (≤ 2 FA/Hour) FARs. Results from the 3½ minute background array merely scatter about the standard curve.

The results of utilization of adaptive noise pre-whitening weights are shown in figures 4-6. Figure 4 illustrates the effects of the adaptive weights with the normal 14 minute background. It also suggests an improvement in performance at the lower FARs. When the adaptive weights are combined with the 7-minute background (figure 5), the improvement is even more marked. The dashed line estimates the overall change in performance. It shows more than 50% reduction in FAR at the lower rates and it highlights the systematically better performance on NORSAR data compared to Pinedale under these controls. The limited results of Figure 6 show a return of performance levels for the NORSAR data to near standard levels when the adaptive weights are used with a 3½ minute background array.

The effects of changing the length of the overlap period of the transforms are illustrated in Figures 7-9. A reduction of the overlap to 0.8 seconds, shown in figure 7, yields a general decrease in performance quality with the results again most evident at the low FARs. An increase in the overlap to 2.4 seconds is shown in Figures 8 and 9 with the latter requiring 3 consecutive transforms above threshold for a detection instead of only 2. Figure 8 shows no change in performance level while figure 9 shows a 40-50% improvement in the FAR for moderate rates, but an increase in the FAR for very low rates. The standard runs transform every data point twice; 0.8 second overlap runs transform only half the data twice; and 2.4 second overlaps transform every data point 4 times. A major effect is observed in the computational time required for these runs. When comparing to standard runs, the 0.8 second overlap runs require about 30% less time than standard, while the 2.4 second overlaps require about 75% more time. None of the runs illustrated in the previous figures varied more than ±10% from the standard time.

Table 1. Walsh Detector Control Conditions

Results in Figure	Walsh Detector Control Conditions									
	7 minute background	3½ minute background	Adaptive noise filter	0.8 second transform overlap	2.4 second transform overlap	3 transforms over threshold	High frequency added	High frequency removed	Low frequency added	Low frequency removed
2	N,P									
3		N,P								
4			N,P							
5	N,P		N,P							
6		N	N							
7				N,P						
8					N,P					
9					N,P	N,P				
10							P			
11								P		
12									P	
13										P
14							N			
15								N		
16									N	
17										N
18					N			N		
19					N				N	
20					N					N

N - indicates run conditions made on NORSAR data
P - indicates run conditions made on Pinedale data

The effects of varying the detection passband at Pinedale are shown in Figures 10-13. They indicate that the passband can be broadened from 0.94 - 1.88 Hz (6-13 Walsh coefficients) to 0.94-2.19 Hz (6-15), or narrowed to 0.94-1.25 Hz (6-9 Walsh coefficients) without significantly affecting the detector performance on these test data. The lower frequency effects, either broadening or narrowing, show significant changes.

The effects of varying the detection passband at NORSAR are shown in figures 14-17. They also show that the high frequency end of the passband can be broadened from 1.25-3.75 Hz (8-25 Walsh coefficients) to 1.24-4.38 Hz (8-29), or narrowed to at least 1.25-3.13 Hz (8-21 Walsh coefficients) without significant effects on the detection performance. The low frequency end of the passband is not as sensitive as for Pinedale. Figures 16 and 17 show that the low frequency cut-off can be extended to 0.31 Hz or raised to at least 2.19 Hz (2 and 14 Walsh coefficients, respectively) without affecting the performance.

Figures 18-20 present the effects of varying the passband at NORSAR when using a 2.4 second transform overlap. A solid diamond on each figure depicts the starting point for the normal coefficient range with the 2.4 second overlap. The data show the same general insensitivity to the passband limits as the previous figures for NORSAR. The upper passband limit may be reduced to near 2.5 Hz (17 Walsh coefficient) and the lower limit reduced to 0.31 or raised to 2.19 Hz (2 and 14 Walsh coefficients, respectively) without significantly affecting the detector performance. It is obvious, however, that the scatter of the data is greater for the 2.4 second transform overlap than for the normal 1.6 second overlap.

Variation of the detection passband width also has significant effects upon the computational time. The CPU time used for Pinedale changes by +(-)12% per pair of Walsh coefficients added (subtracted). Because of the wider normal passband for NORSAR, the observed change in only +(-)7% per pair of Walsh coefficients.

2.2 CONCLUSIONS

The general results from the multitude of test runs made on both the NORSAR and Pinedale data tapes indicate great stability in the performance of the Walsh seismic event detection algorithm under a wide variety of control conditions. Specific results show:

- Background Time Period - The best overall performance for the detector was achieved with a background noise sampling of 7 minutes. This probably is dependent on station location,and other stations could have greater or lesser time constants which approximate their noise fluctuation rates.

- Adaptive Pre-whitening Weights - Adaptive noise weights appear to give some general improvement in the detector performance. This is most evident in Figure 5 where adaptive weights were combined with a 7-minute background array. Perhaps of greater importance is the fact that the adaptive weights do not degrade the performance of the detector. This means that they can be routinely used in the detector and will, therefore, remove the rather substantial seasonal fluctuations in the frequency content of the noise observed at many stations. Without this adaptivity, analysts would have to periodically evaluate the noise spectra and make corresponding noise filter adjustments to keep the detector operating near optimal efficiency.

- Transform Overlap Width - Improved detection results were obtained with a 2.4 second transform overlap while extending the number of consecutive transforms above threshold to 3 in order to maintain the 4.8 second time frame of significant energy. Effectively, this time frame requirement indicates most signals were more than 3.2 seconds in length - but not necessarily greater than 4.8 seconds, while most noise fluctuations were significantly less than 4.8 seconds. These criteria may be more characteristic of the data available on the test tape than for events in general. Because this large transform overlap processes each data point 4 times, this mode of detection required about 75% more computational time. Its usage may be controlled by the available computer power.

- Detection Passband - The detector showed a general insensitivity to changes in the detection passband. This stability in the results, however, may be controlled by the prior processing of the anti-aliasing and recursive filters as well as the basic shape of the system response, rather than be inherent in the detector. Additional work is necessary to define the exact relationships. Detailed investigation of the particular events which were affected by the changes in the passband showed that, indeed, when the passband was extended or reduced, low level events which were rich in the frequencies of the affected region were either added or removed from the group of detected events. Similarly, events which had less of the frequencies of the adjusted part of the passband became harder or easier to detect, respectively, and so were also subject to removal or addition to the detection group. From the efficiency point of view, the ~10% additional CPU time necessary to process each additional pair of Walsh coefficients suggests that the detection passband be kept to the minimal width necessary to observe the desired seismic events. In fact, it may be faster to process data in two narrow passbands than a single broad passband.

3. DESIGN OF A WALSH DETECTION SYSTEM FOR UNATTENDED FIELD DEPLOYMENT

All components of the remote Walsh algorithm seismic detection system have been assembled and tested for operational stability. The system is designed to operate unattended at a remote location. It utilizes a single channel detector to flag potential seismic events and multiplexes a step function onto a telephone line with the analog data to mark detections. The system could equally well set a flag to accumulate digital data during the course of the seismic event. Table 1 gives the important characteristics of the field system, compares them to the system operated at NORSAR, and denotes the principle effects of the differences.

Table 2. Comparison of NORSAR Walsh and New Field Walsh Detection Systems

Characteristic	Effect
Basic Program - NORSAR is RAM based Field system is ROM based	Power outages shut down both systems. When power is restored, the field system comes up and automatically begins data processing. The NORSAR system must be reloaded and started by an operator.
ADC - NORSAR requires outside timing Field system uses internal timer	The field system integrated ADC unit consumes less power and has a relative time base
Peripheral Equipment - NORSAR required Helicorder, timer, CRT, disk controller and printer Field system requires none	The field system is designed to do detection analysis only on site. Data is to be displayed and/or recorded at some main processing center.
Number of Detection Channels NORSAR processes up to 10 Field system processes 1	The voting confirmation of the NORSAR detector can provide a lower detection threshold at a lower False Alarm Rate (FAR).

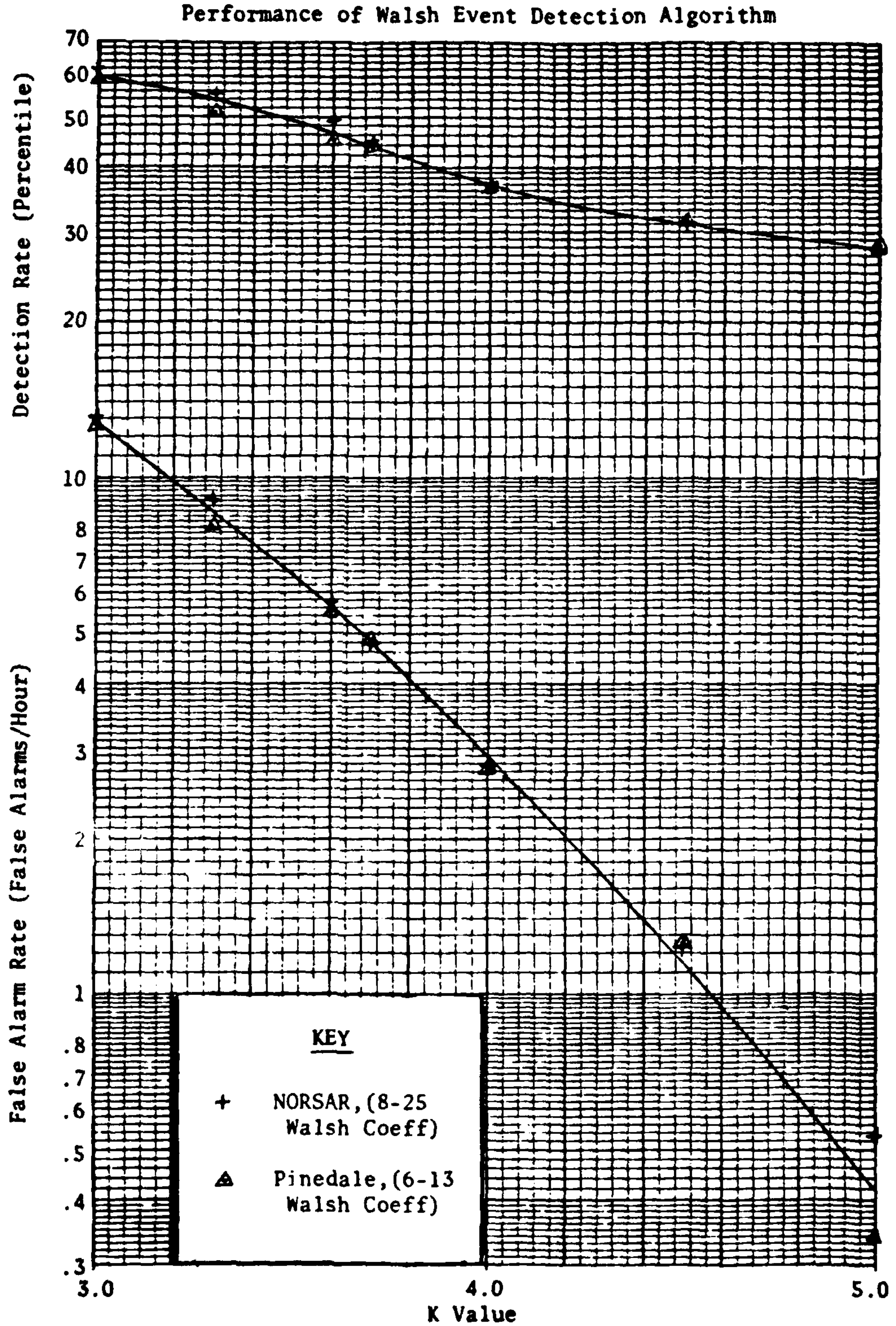

Figure 1. 'Standard' Performance of Walsh Detection Algorithm at NORSAR and Pinedale

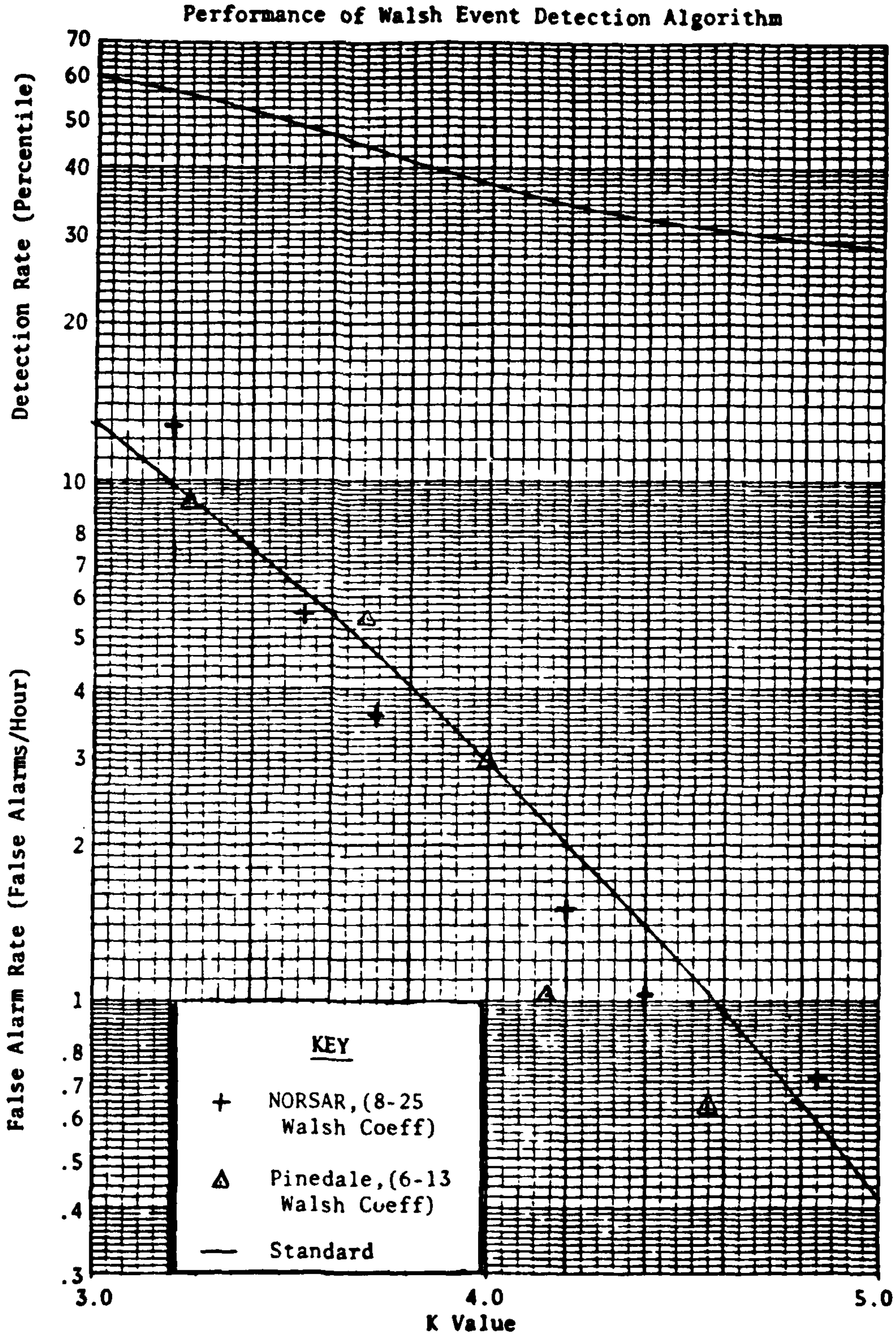

Figure 2. Effects of a 7 Minute Background Array

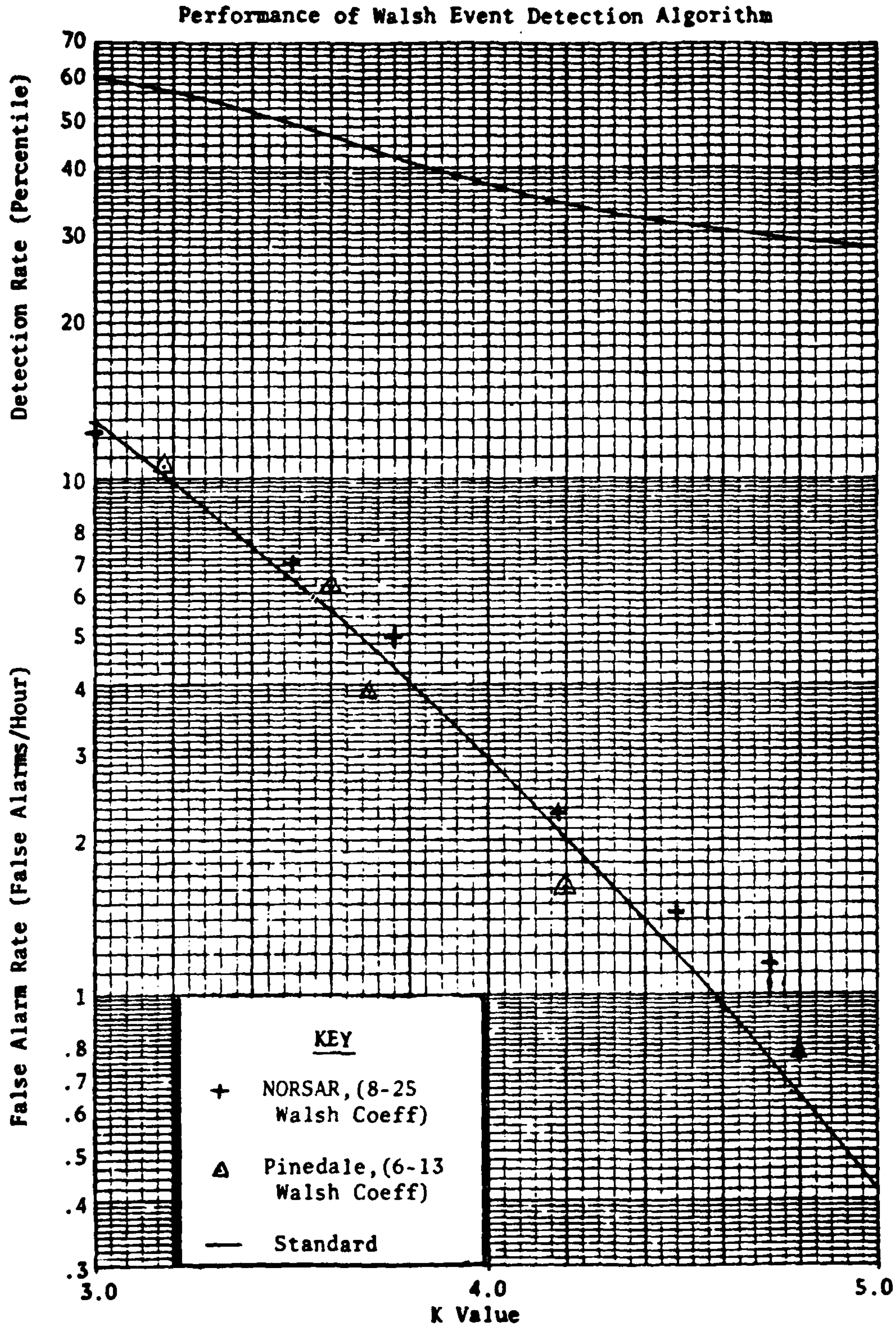

Figure 3. Effects of a 3 1/2 Minute Background Array

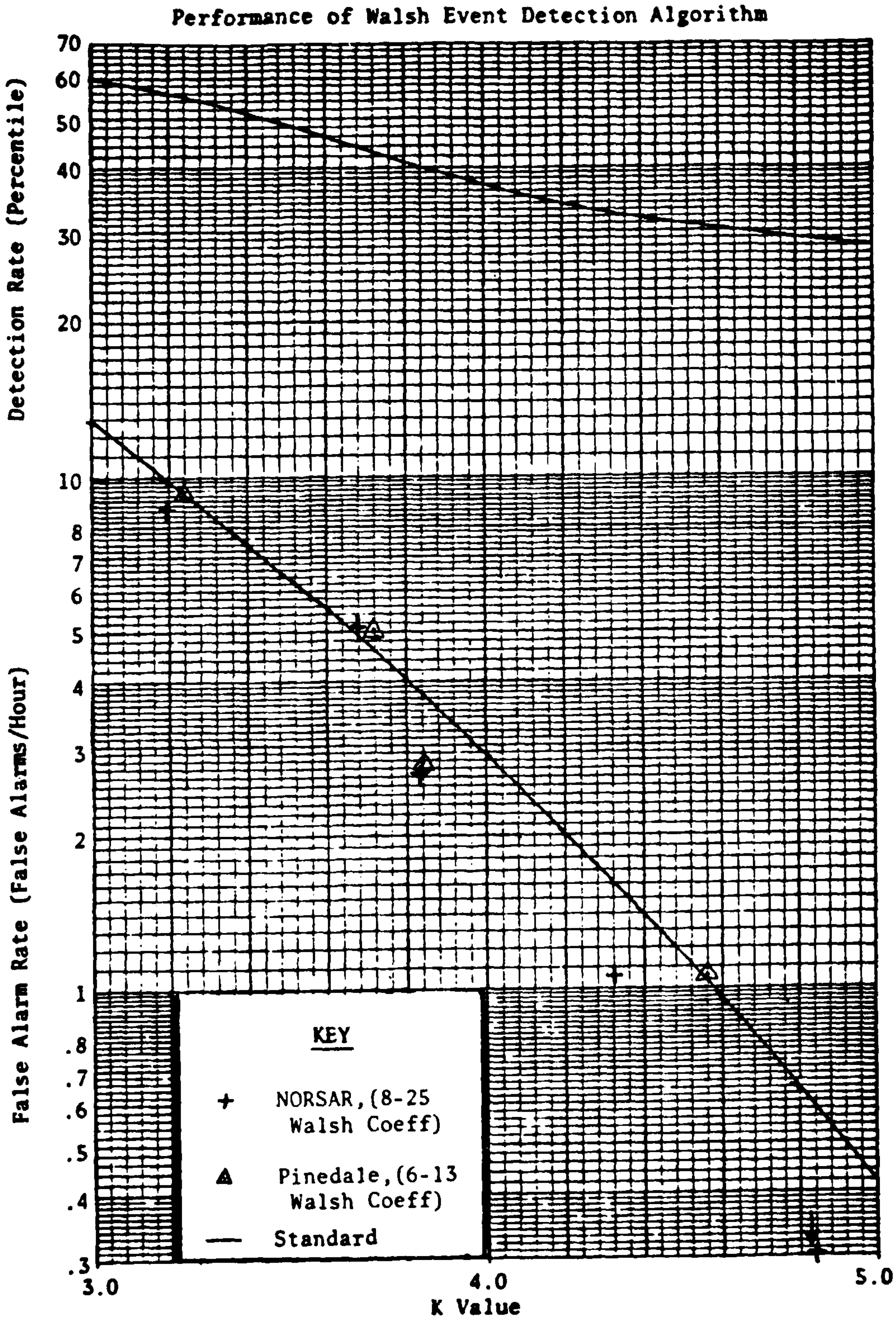

Figure 4. Effects of Adaptive Noise Filters

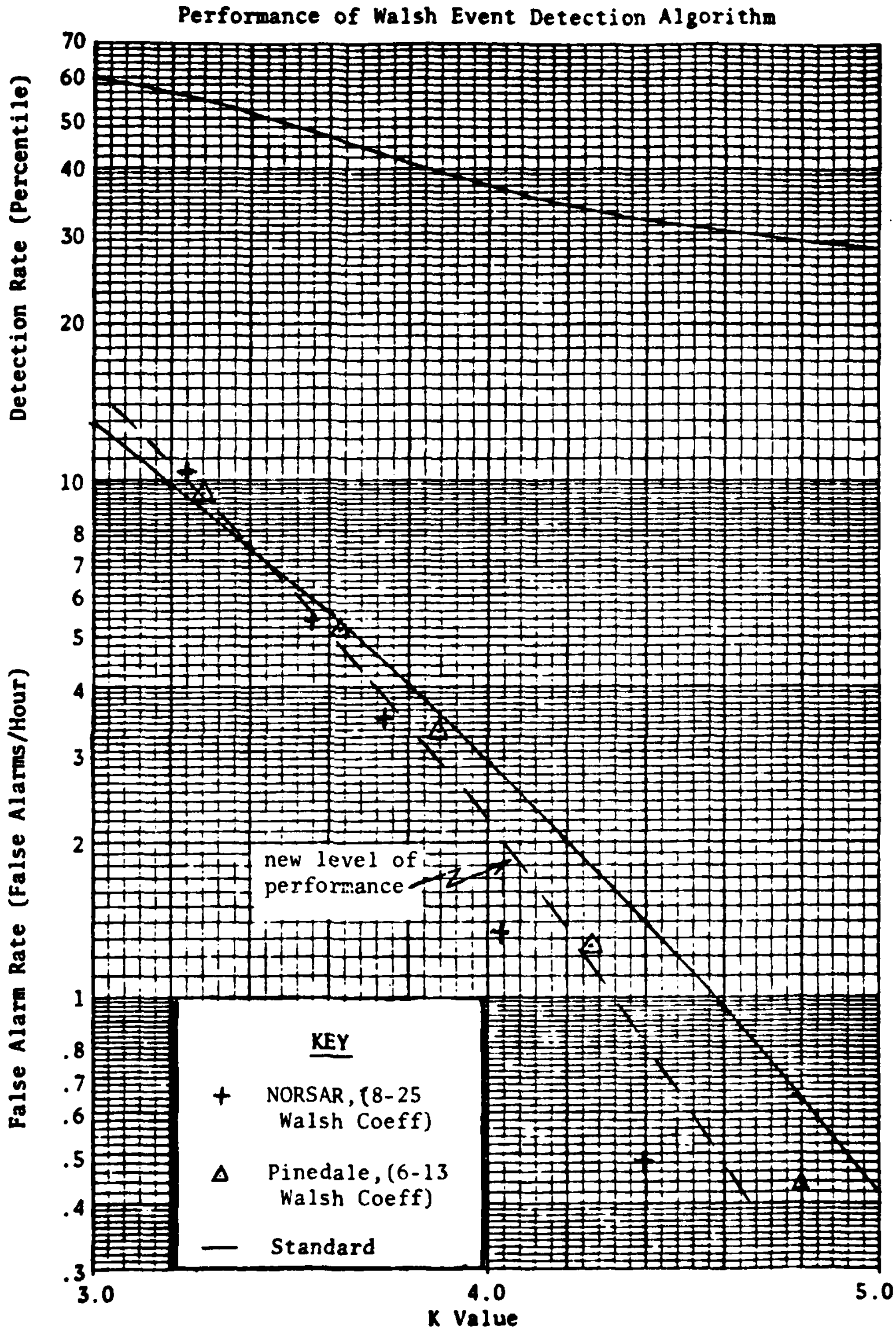

Figure 5. Effects of a 7 Minute Background with an Adaptive Filter

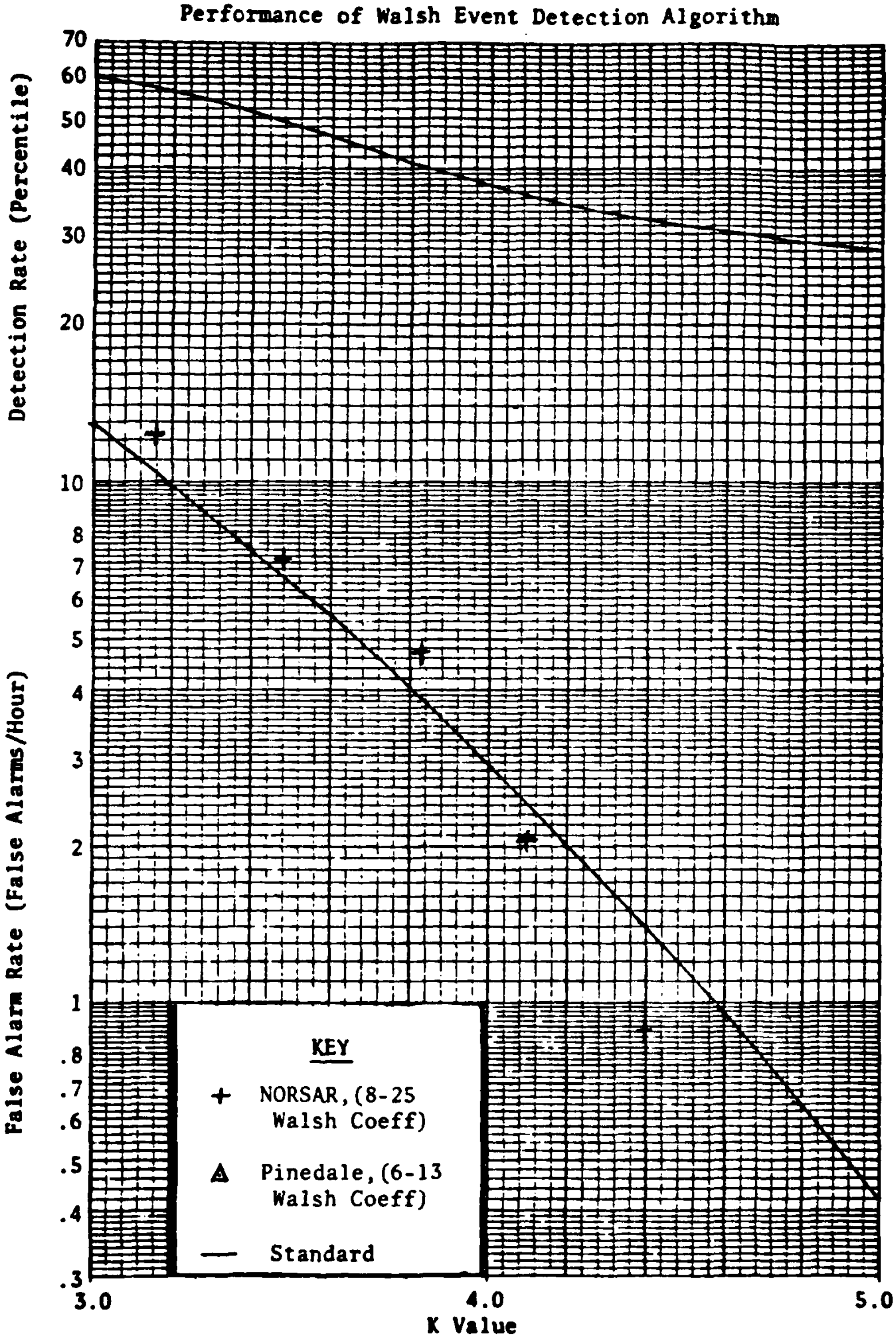

Figure 6. Effects of a 3 1/2 Minute Background with an Adaptive Filter

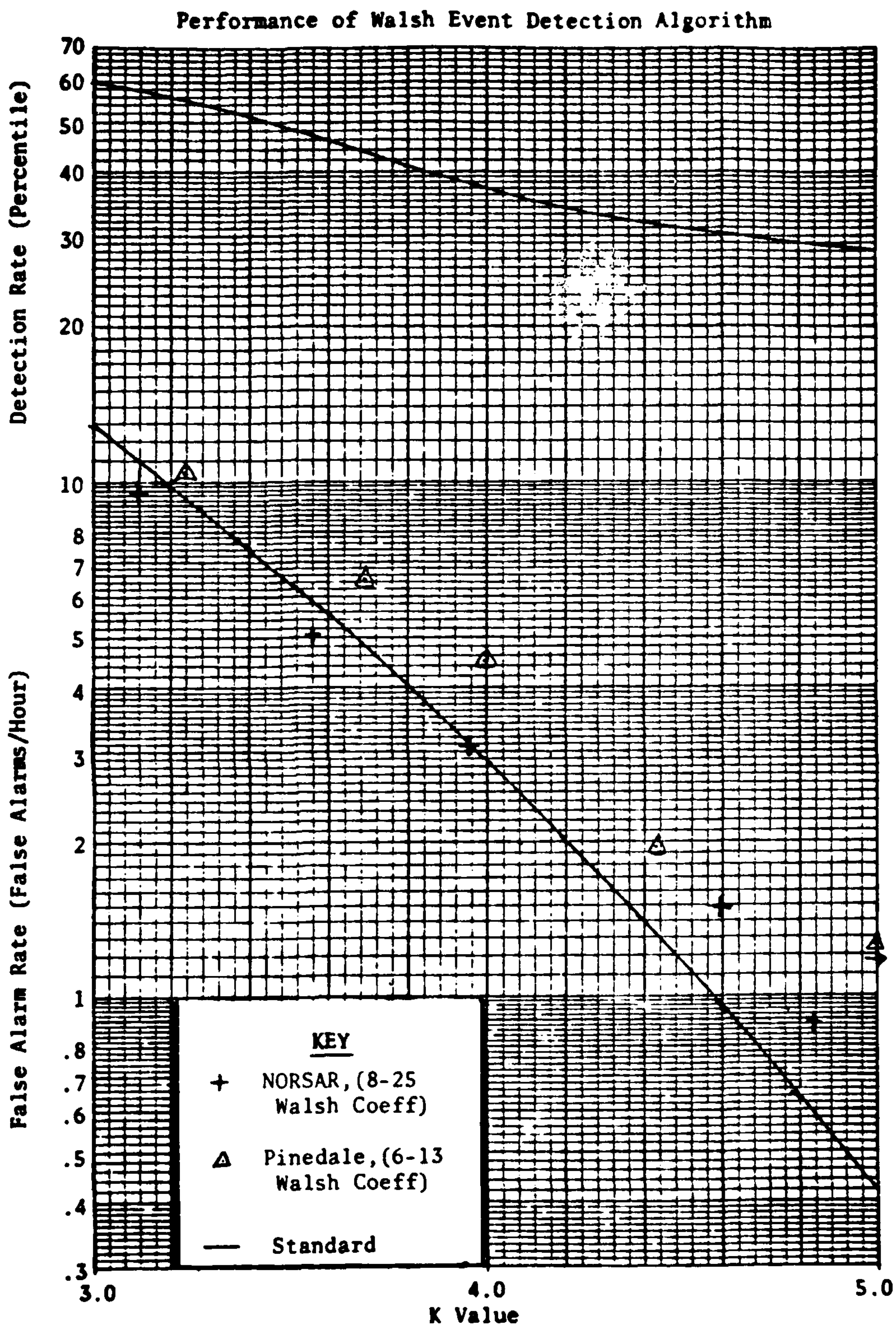

Figure 7. Effects of a 0.8 Second Transform Overlap

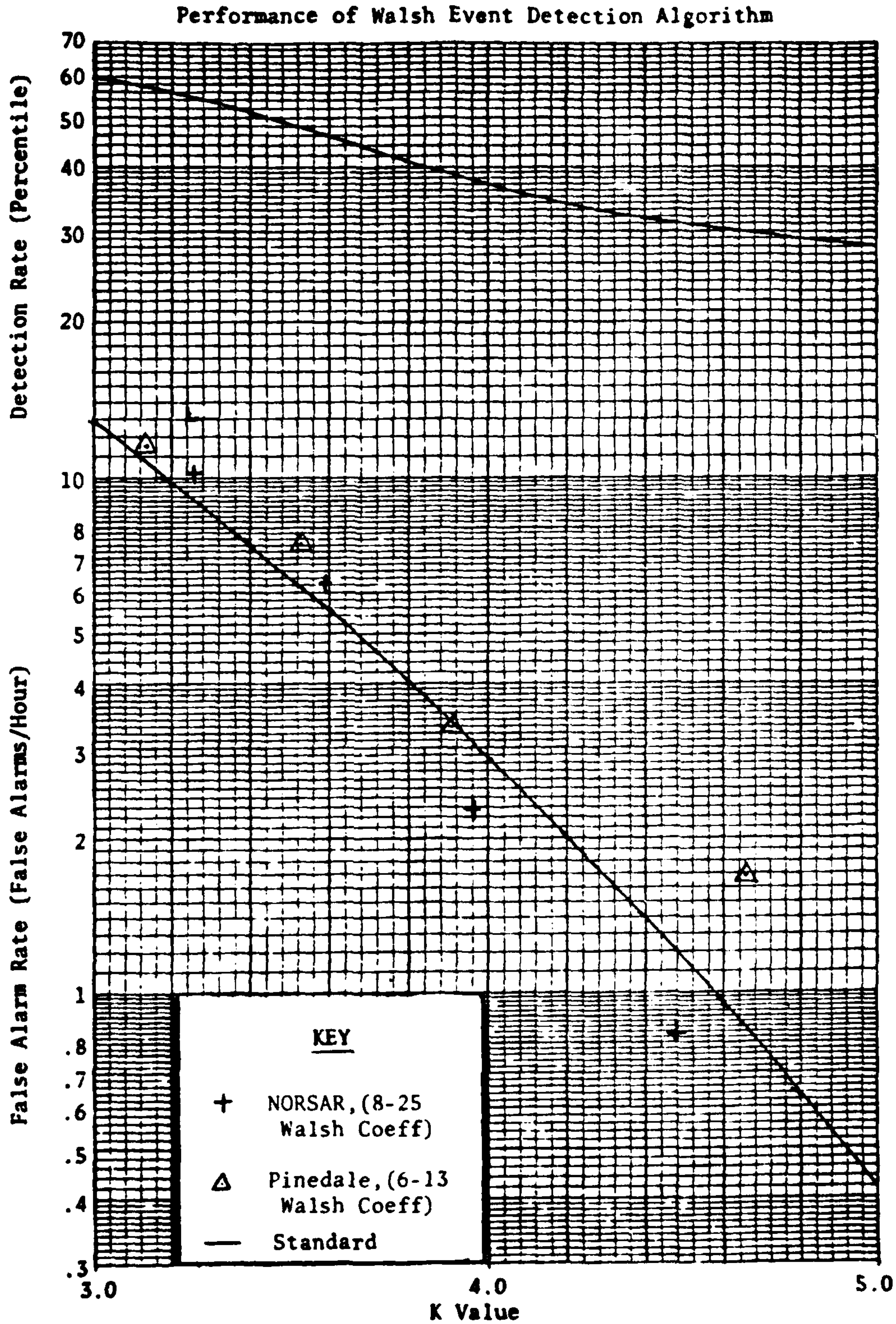

Figure 8. Effects of a 2.4 Second Transform Overlap

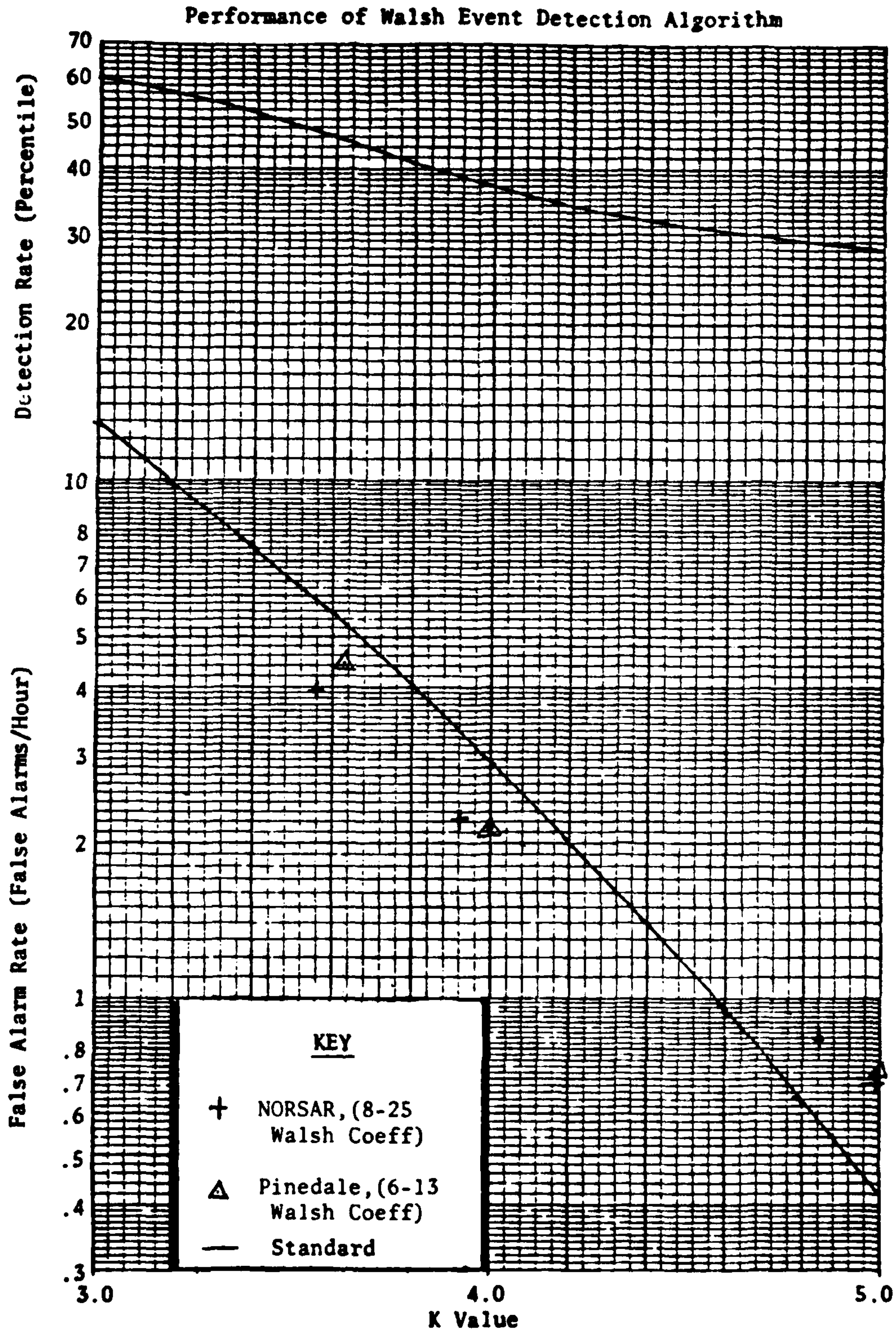

Figure 9. Effects of a 2.4 Second Transform Overlap with 3 Consecutive Transforms above Threshold for Detection

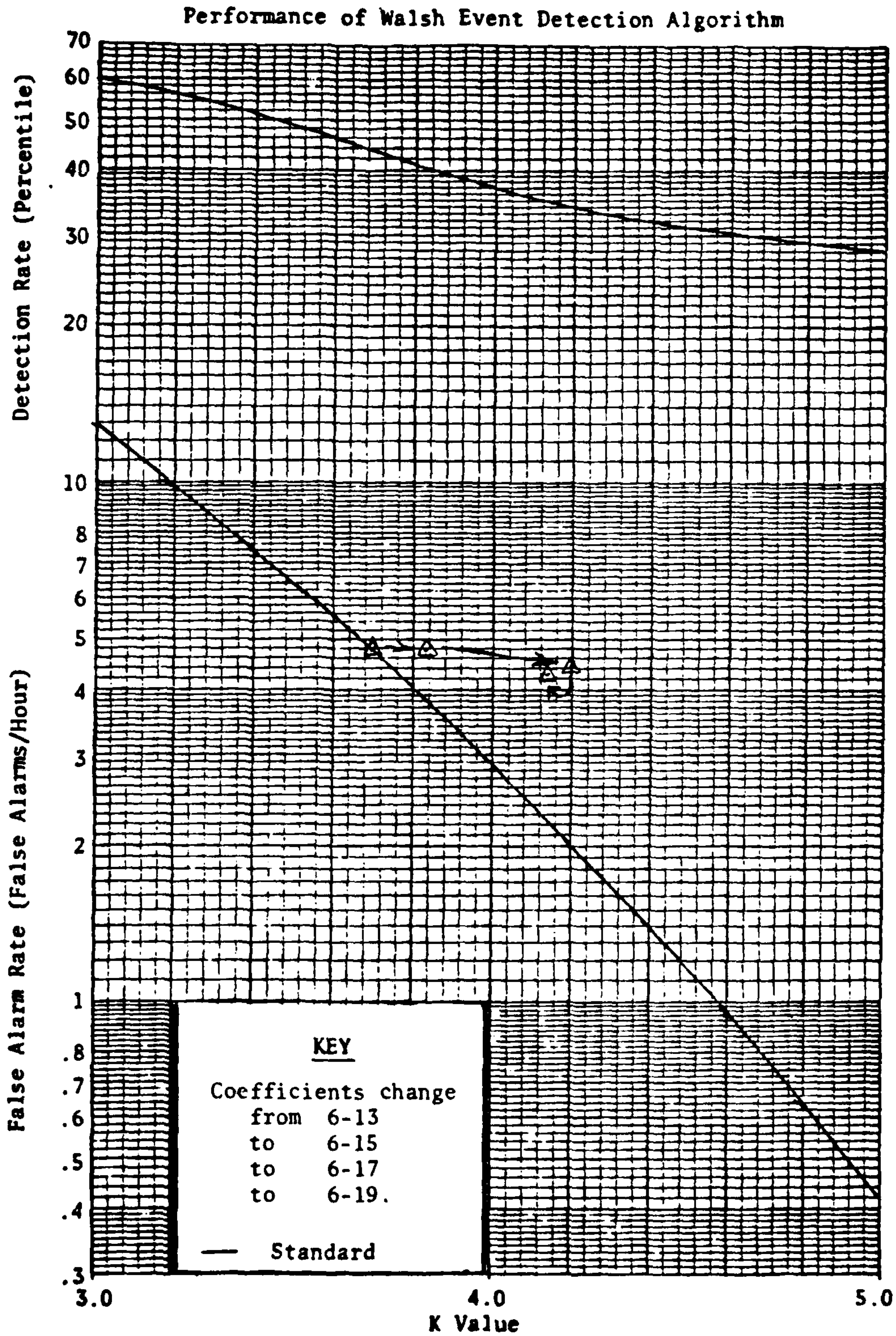

Figure 10. Effects of Adding Higher Frequency Coefficients to Pinedale

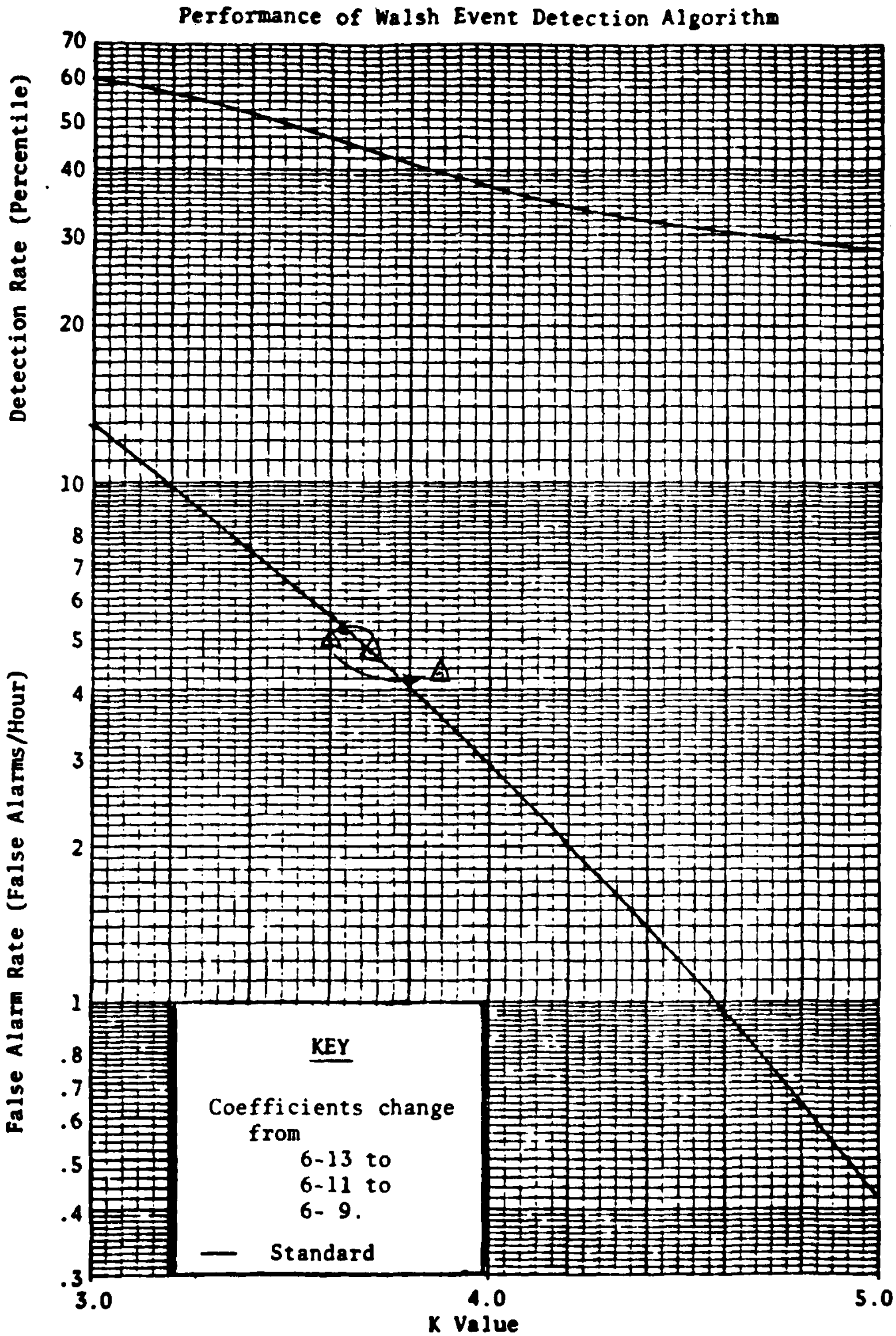

Figure 11. Effects of Removing Higher Frequency Coefficients from Pinedale

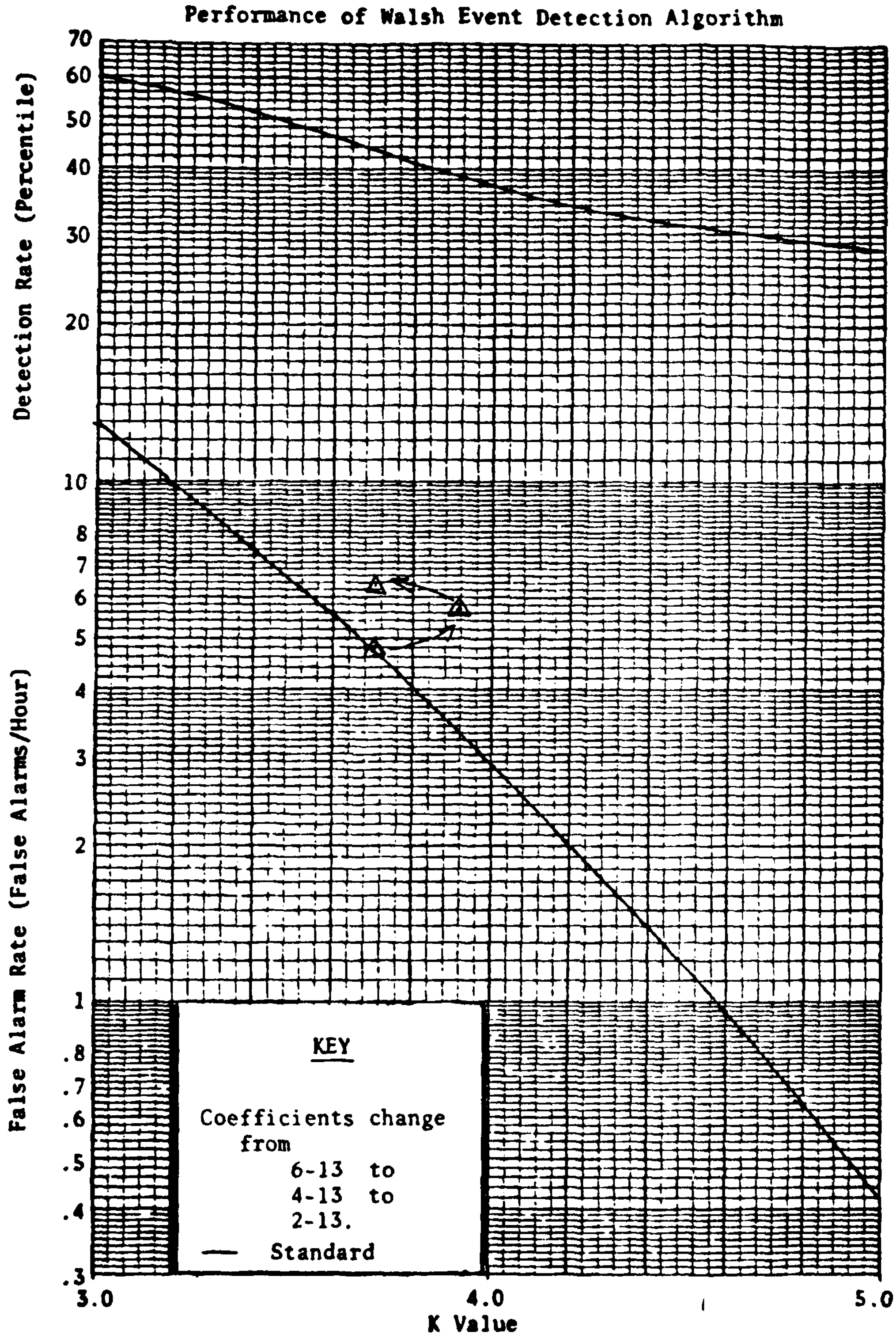

Figure 12. Effects of Adding Lower Frequency Coefficients to Pinedale

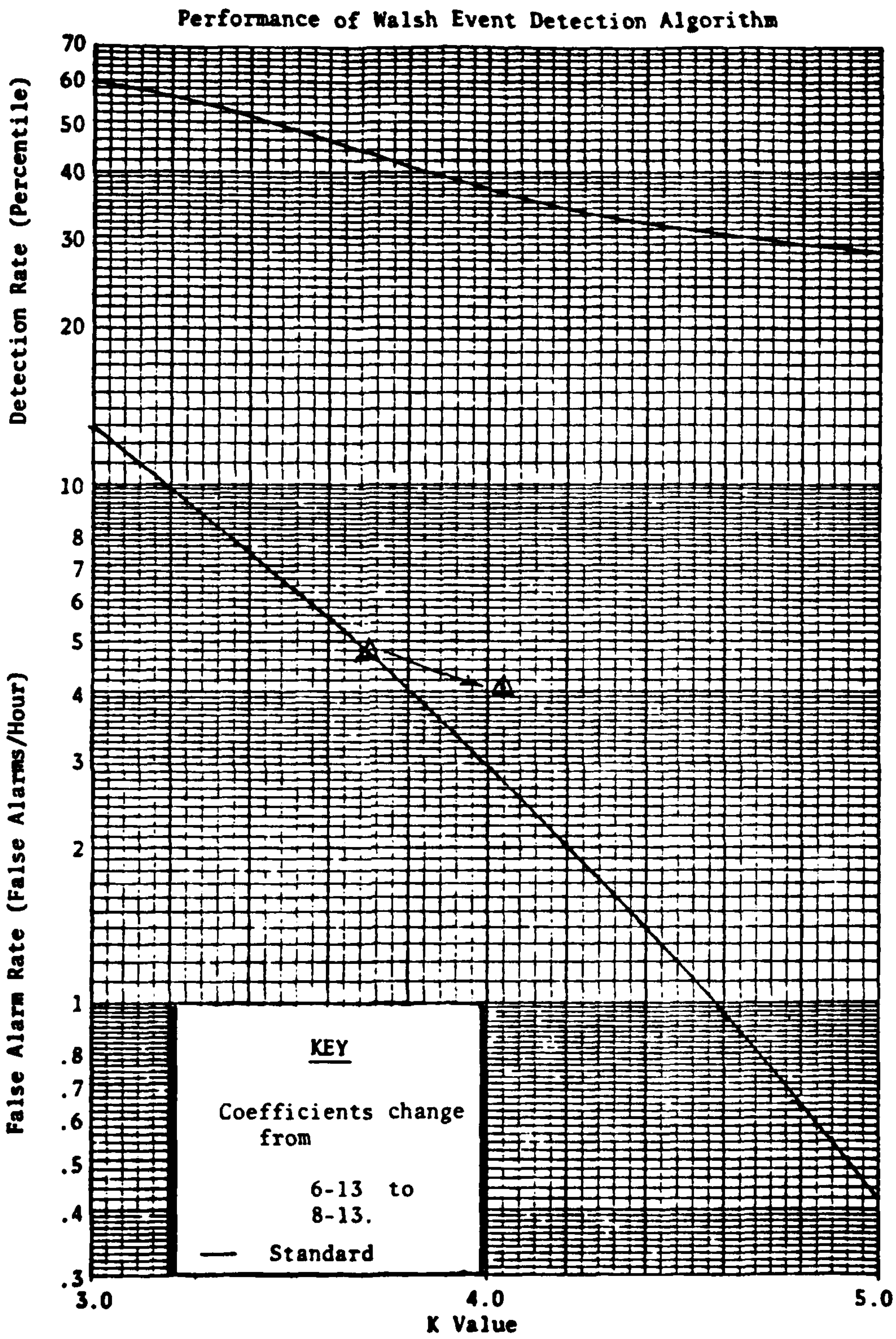

Figure 13. Effects of Removing Lower Frequency Coefficients from Pinedale

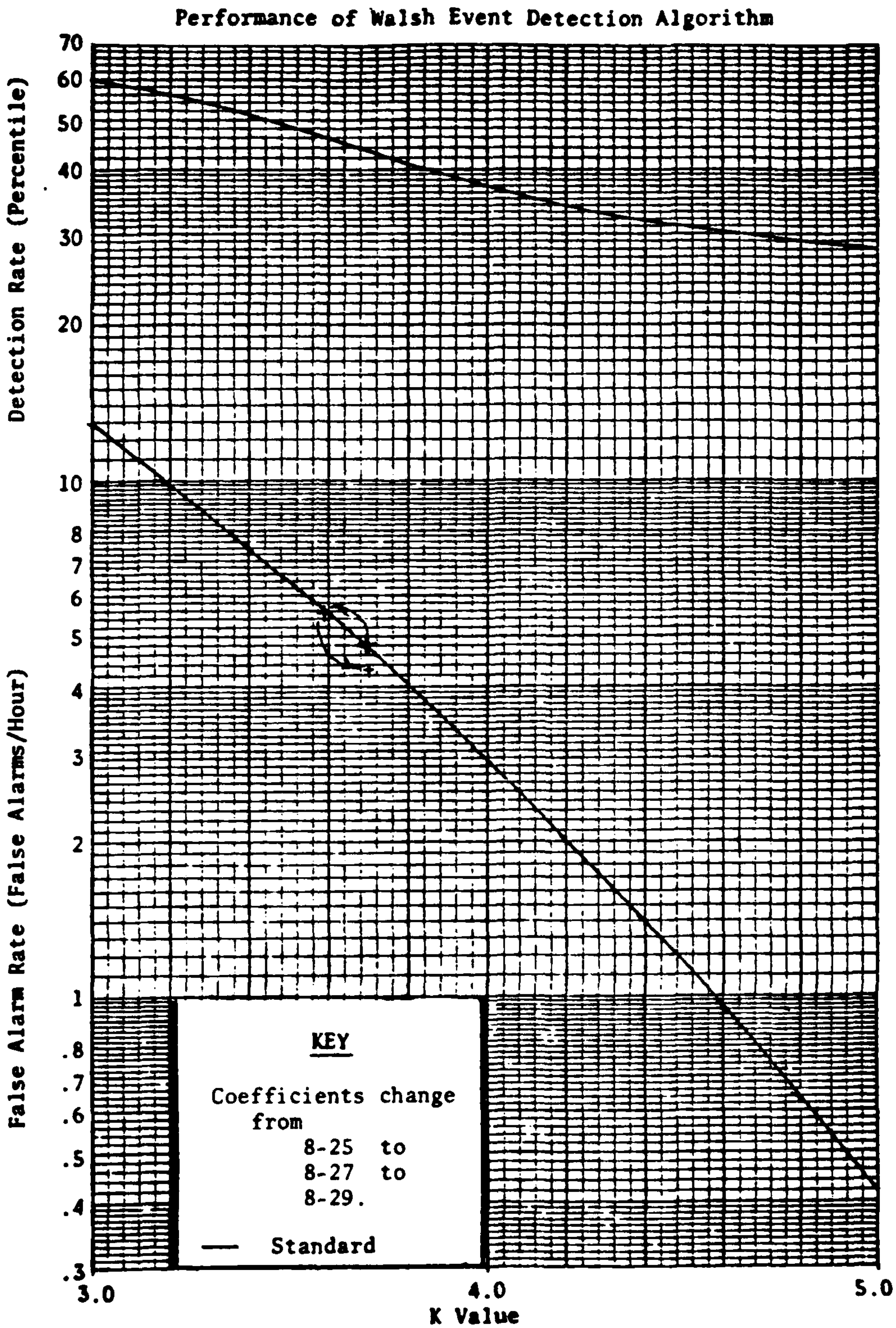

Figure 14. Effects of Adding Higher Frequency Coefficients to NORSAR

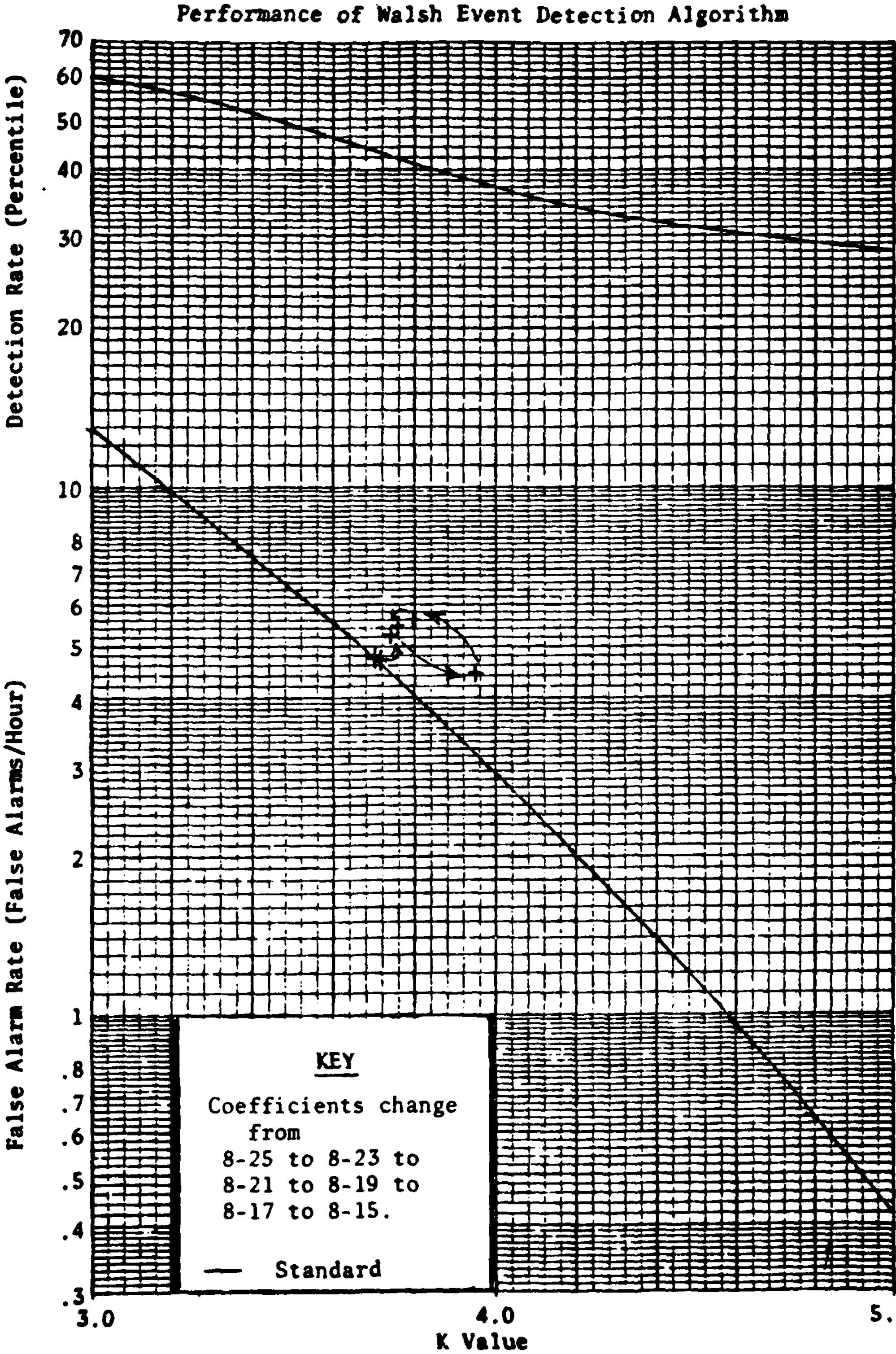

Figure 15. Effects of Removing Higher Frequency Coefficients from NORSAR

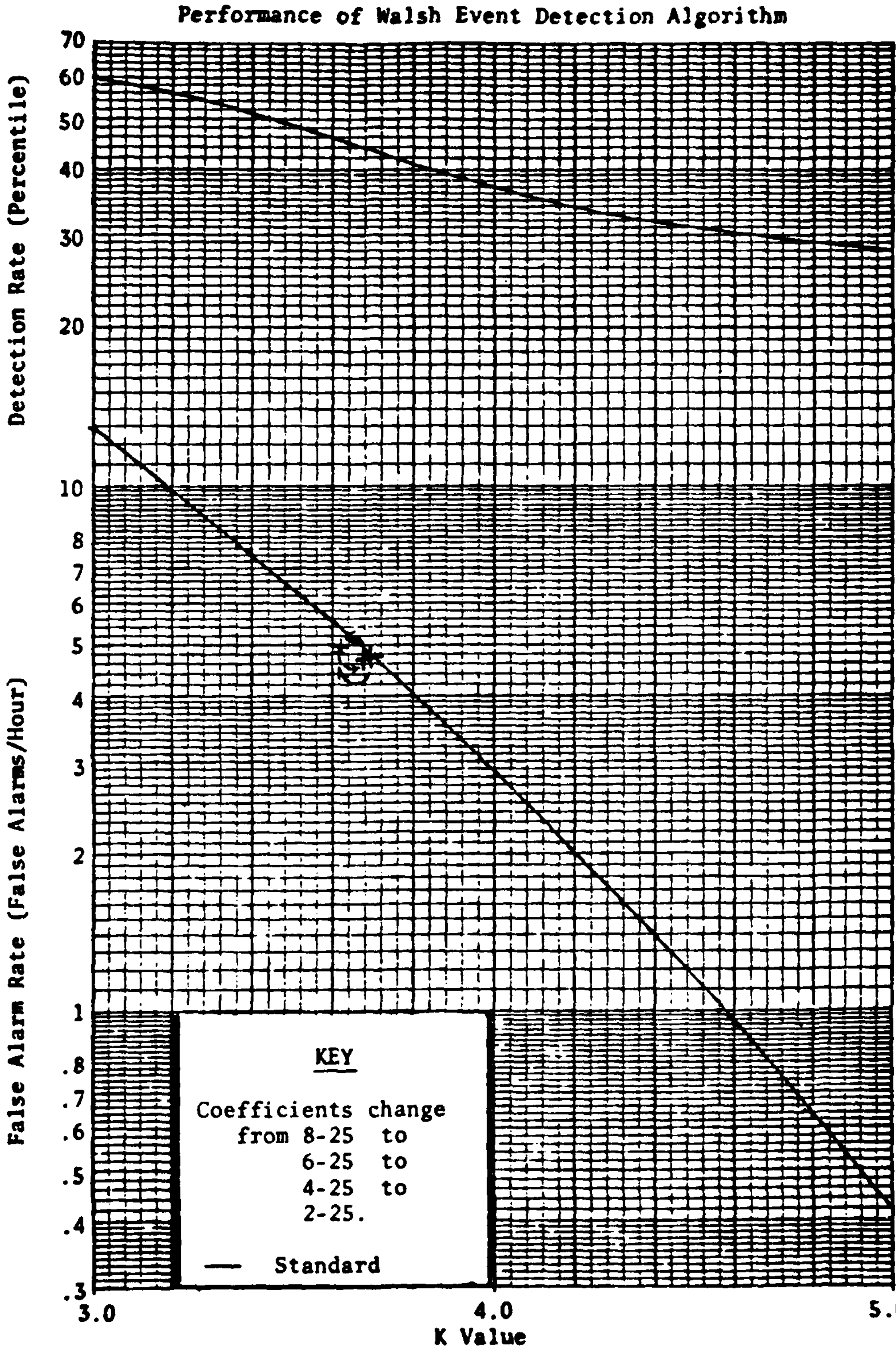

Figure 16. Effects of Adding Lower Frequency Coefficients to NORSAR

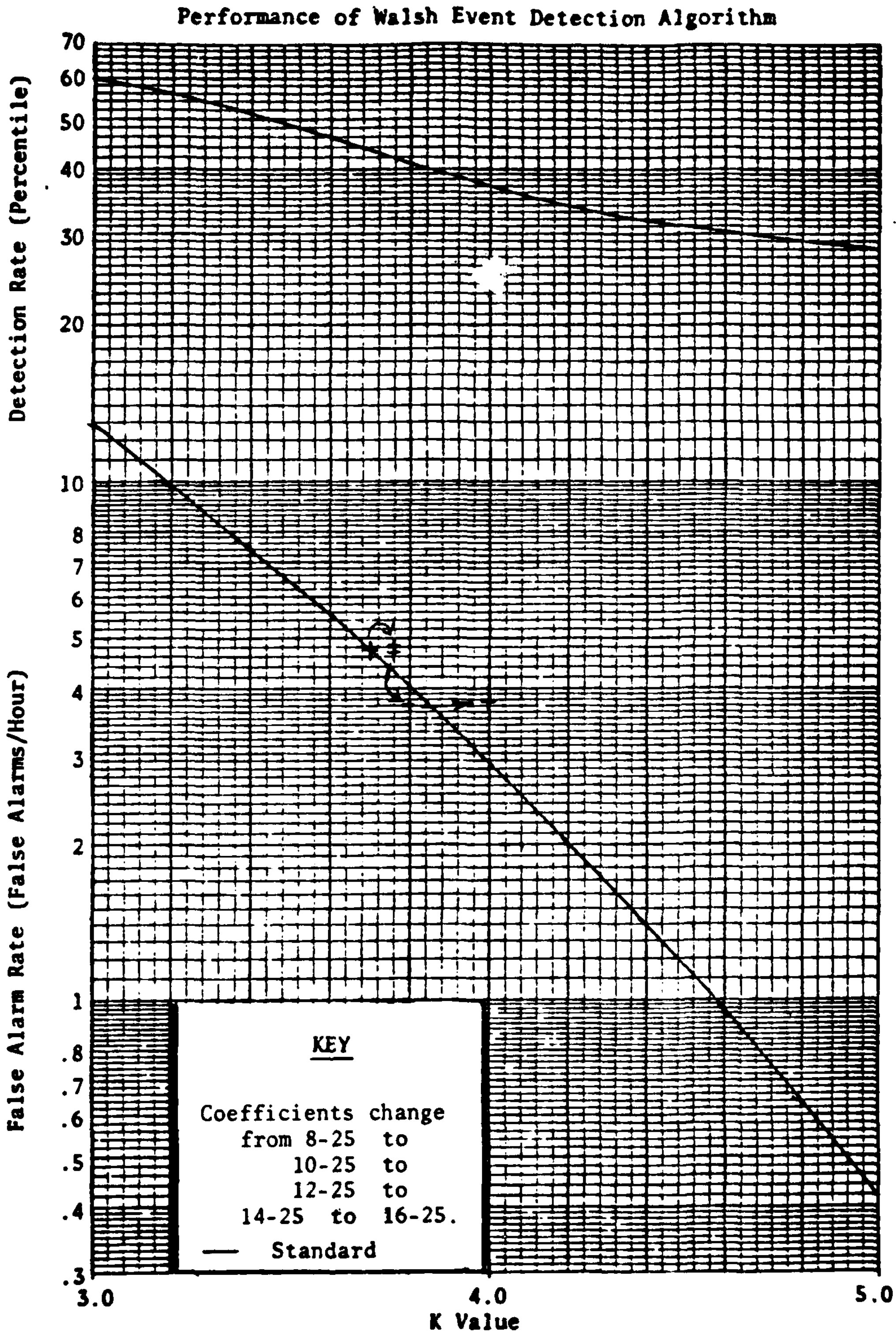

Figure 17. Effects of Removing Lower Frequency Coefficients from NORSAR

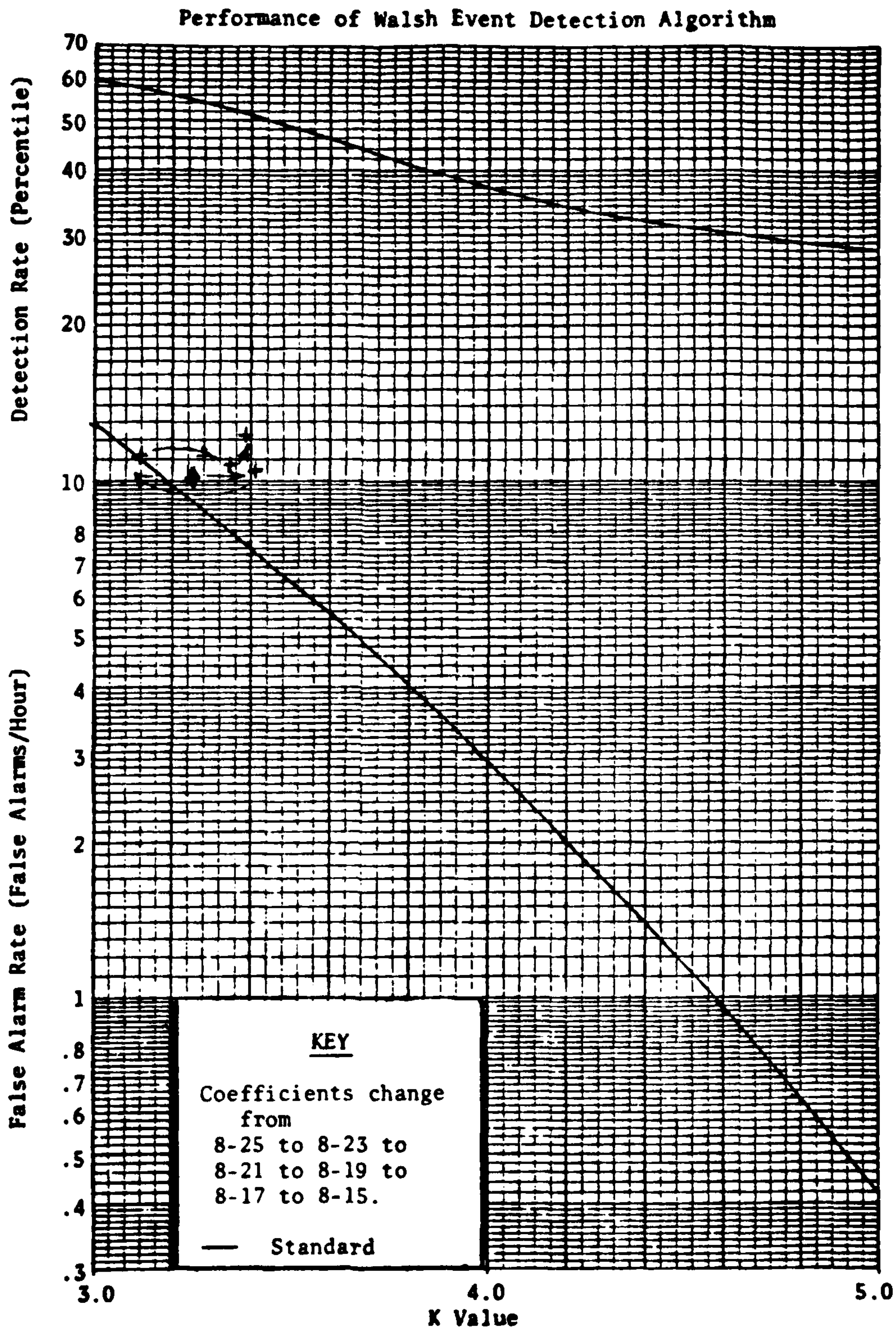

Figure 18. Effects of Removing Higher Frequency Coefficients from NORSAR with a 2.4 Second Transform Overlap

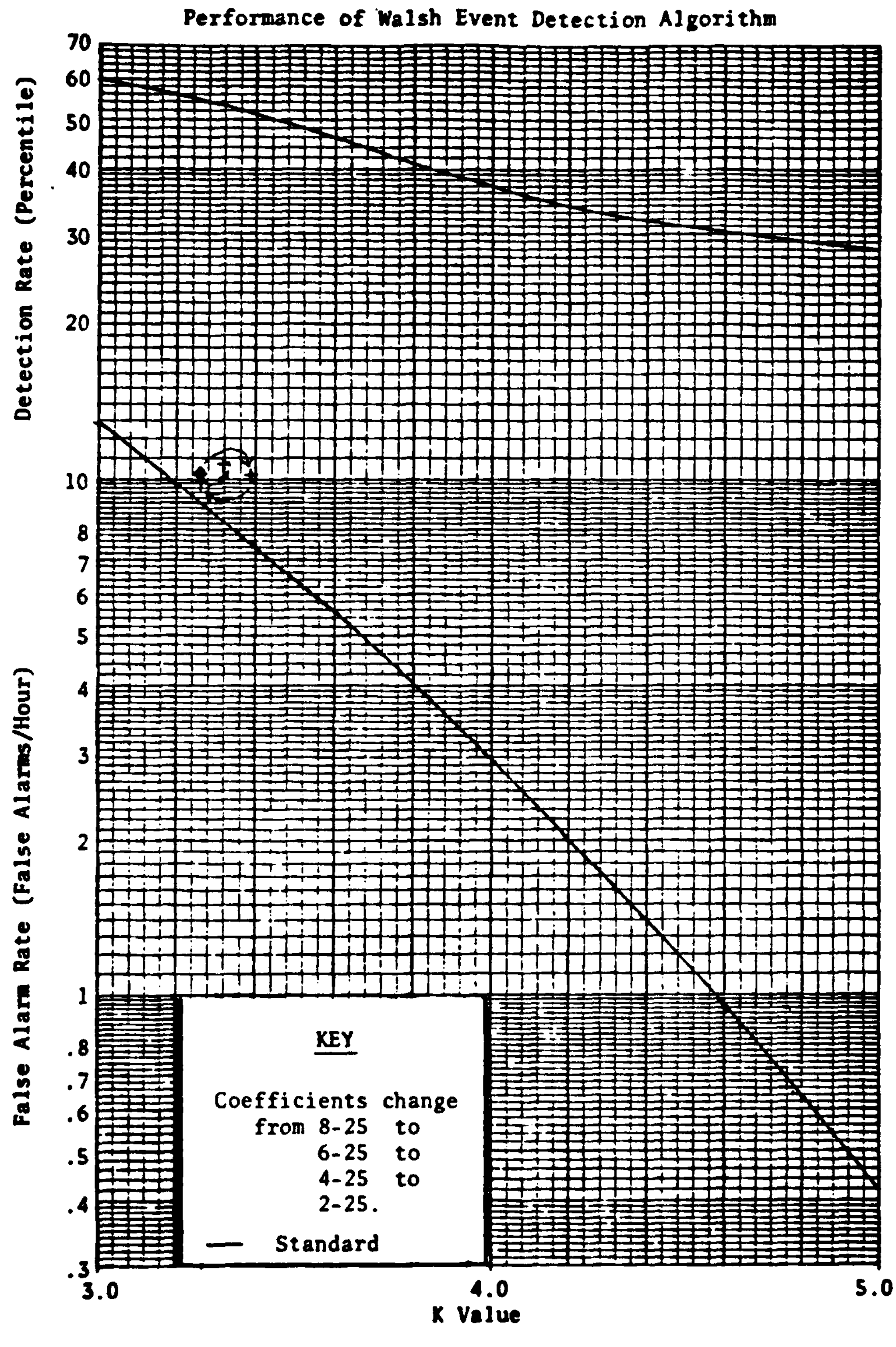

Figure 19. Effects of Adding Lower Frequency Coefficients to NORSAR with a 2.4 Second Transform Overlap

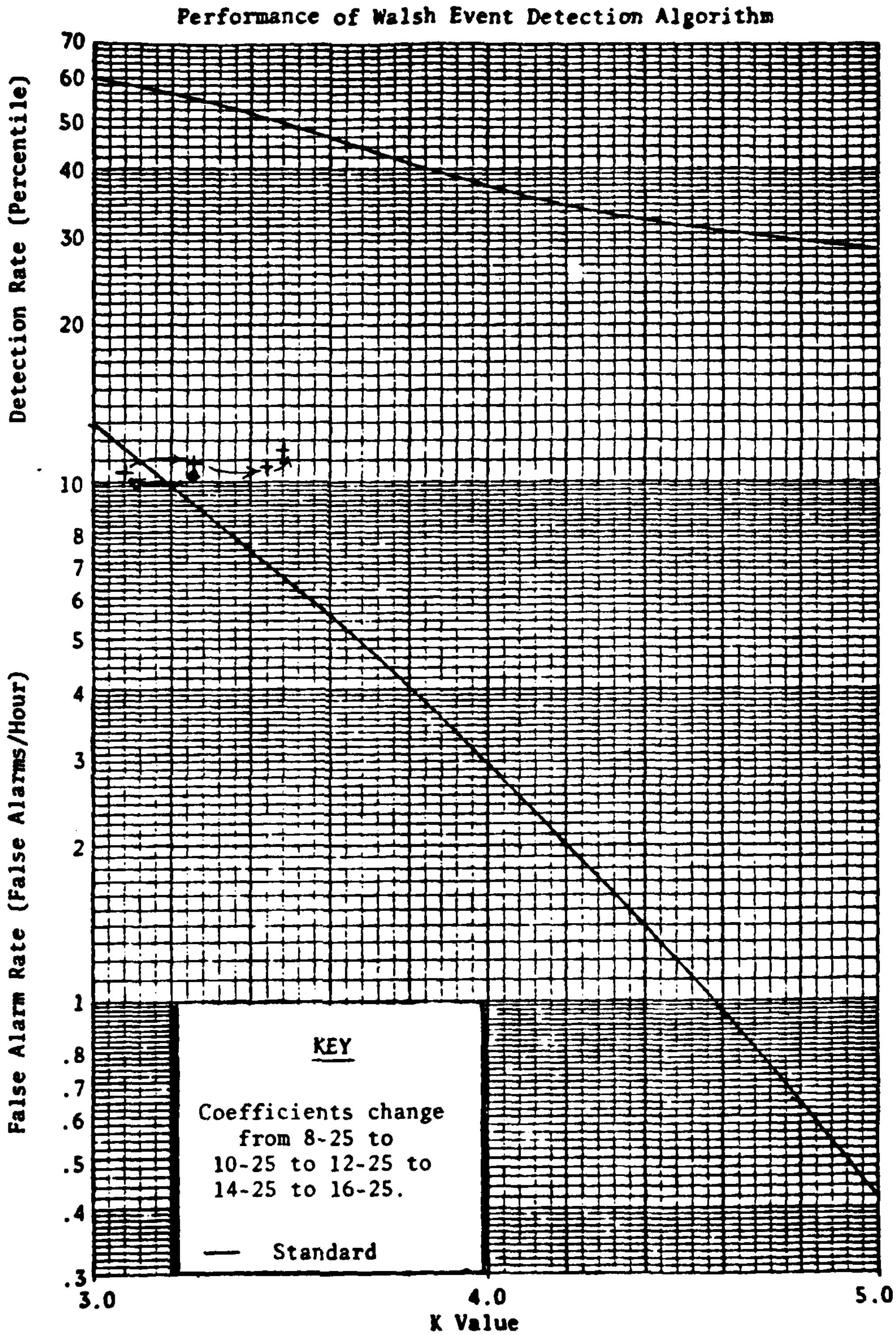

Figure 20. Effects of Removing Lower Frequency Coefficients from NORSAR with a 2.4 Second Transform Overlap