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An On-Line Seismometer Array Processor

S V New

Recommended for issue by

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Approved

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Some Metric and SI Unit Conversion Factors

(Based on DEF STAN 00-11/2 "Metric Units for Use by the Ministry of Defence", DS Met 5501 "AWRE Metric Guide" and other British Standards)

Quantity	Unit	Symbol	Conversion
Basic Units			
Length	metre	m	1 m = 3.2808 ft 1 ft = 0.3048 m
Mass	kilogram	kg	1 kg = 2.2046 lb 1 lb = 0.45359237 kg 1 ton = 1016.05 kg
Derived Units			
Force	newton	$N = kg\ m/s^2$	1 N = 0.2248 lbf 1 lbf = 4.44822 N
Work, Energy, Quantity of Heat	joule	J = N m	1 J = 0.737562 ft lbf 1 J = 9.47817×10^{-4} Btu 1 J = 2.38846×10^{-4} kcal 1 ft lbf = 1.35582 J 1 Btu = 1055.06 J 1 kcal = 4186.8 J
Power	watt	W = J/s	1 W = 0.238846 cal/s 1 cal/s = 4.1868 W
Electric Charge	coulomb	C = A s	-
Electric Potential	volt	V = W/A = J/C	-
Electrical Capacitance	farad	F = A s/V = C/V	-
Electric Resistance	ohm	Ω = V/A	-
Conductance	siemen	$S = 1\ \Omega^{-1}$	-
Magnetic Flux	weber	Wb = V s	-
Magnetic Flux Density	tesla	$T = Wb/m^2$	-
Inductance	henry	H = V s/A = Wb/A	-
Complex Derived Units			
Angular Velocity	radian per second	rad/s	1 rad/s = 0.159155 rev/s 1 rev/s = 6.28319 rad/s
Acceleration	metre per square second	m/s^2	1 m/s^2 = 3.28084 ft/s^2 1 ft/s^2 = 0.3048 m/s^2
Angular Acceleration	radian per square second	rad/s^2	-
Pressure	newton per square metre	N/m^2 = Pa	1 N/m^2 = 145.038×10^{-6} lbf/in^2 1 lbf/in^2 = 6.89476×10^3 N/m^2
	bar	bar = 10^5 N/m^2	- 1 in. Hg = 3386.39 N/m^2
Torque	newton metre	N m	1 N m = 0.737562 lbf ft 1 lbf ft = 1.35582 N m
Surface Tension	newton per metre	N/m	1 N/m = 0.0685 lbf/ft 1 lbf/ft = 14.5939 N/m
Dynamic Viscosity	newton second per square metre	N s/m^2	1 N s/m^2 = 0.0208854 lbf s/ft^2 1 lbf s/ft^2 = 47.8803 N s/m^2
Kinematic Viscosity	square metre per second	m^2/s	1 m^2/s = 10.7639 ft^2/s 1 ft^2/s = 0.0929 m^2/s
Thermal Conductivity	watt per metre kelvin	W/m K	-
Odd Units*			
Radioactivity	becquerel	Bq	1 Bq = 2.7027×10^{-11} Ci 1 Ci = 3.700×10^{10} Bq
Absorbed Dose	gray	Gy	1 Gy = 100 rad 1 rad = 0.01 Gy
Dose Equivalent	sievert	Sv	1 Sv = 100 rem 1 rem = 0.01 Sv
Exposure	coulomb per kilogram	C/kg	1 C/kg = 3876 R 1 R = 2.58×10^{-4} C/kg
Rate of Leak (Vacuum Systems)	millibar litre per second	mb l/s	1 mb = 0.750062 torr 1 torr = 1.33322 mb

*These terms are recognised terms within the metric system.

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SUMMARY

The design, development and performance of an On-line Seismometer Array Processor (OSAP) is described. The purpose of an OSAP is to: receive the digitised signals (sampled 20 times per second) from each of 20 seismometers of a 10 km aperture array of the UK-type; detect seismic signals with a signal-to-noise ratio of about two or greater; estimate the epicentres of the sources of the signals; record the signal data on flexible magnetic (floppy) disc and display the signal information on a chart recorder. The prototype OSAP has a Computer Automation Inc LSI-2 minicomputer as its central processor and has been operating satisfactorily at the Eskdalemuir array, Scotland since February 1980. The log-detector algorithm of Weichert is used in the OSAP as this non-linear algorithm is much better than a linear detector at discriminating between detections due to true signals and those due to data errors, particularly large amplitude excursions of short duration ("spikes").

The experience gained in this study suggests that it should be possible to have almost complete automation of the routine running of an array station of the EKA-type, including: the checking of the system for faults; the calibration of the recording system; and the detection and routine analysis of signals of significant amplitude. At such an automated station the staff would be able to concentrate on array maintenance. It seems possible that a fairly inexpensive processor based on two minicomputers could be developed to run the 25 km aperture UK-type arrays and provide all the facilities available in the currently used off-line processors (SASPs).

1. INTRODUCTION

Research over the past twenty years has demonstrated that arrays of seismometers can be used to improve the signal-to-noise ratio of the short period (SP) P waves radiated by earthquakes and explosions. Most of this work has been aimed at finding ways of detecting and identifying low-yield (~ 1 kton) explosions from the seismic signals they generate. To find weak signals hidden in noise requires a processor that can combine in some way the outputs of the seismometers in an array. The obvious way to make such a processor is to build it around a general purpose digital computer and several such processors are in operation. Three of the UK-type arrays (Gauribidanur, India (GBA), Warramunga, Australia (WRA), and Yellowknife, Canada (YKA)) from which MOD(PE), Blacknest receive data are already equipped with such processing systems. These processors are built around Digital Equipment Corporation PDP11s. The processor at the YKA array was developed by the seismology section of the Canadian Department of Energy, Mines and Resources and is described by Weichert and Henger (1). The processors at GBA and WRA - called SASPs - were developed by MOD(PE) and are described by Key, Lea and Douglas (2).

This report describes a second type of array processor developed by MOD(PE) and called an OSAP (On-Line Seismometer Array Processor). the OSAP is built around a Computer Automation Inc LSI-2 and was developed for use at the Eskdalemuir array (EKA) in Scotland, an array that has an aperture (maximum linear dimension) of about 10 km, less than half that of the other three UK-type arrays. The main difference in the processing procedure used for an OSAP from that of a SASP is that the OSAP operates on-line taking the data directly from the outputs of the seismometers of the array and processing the signals as they are received. A SASP, on the other hand, is an off-line processor which takes digital data recorded on a magnetic tape during the preceding 12 h and processes these at 20 times the recording speed; thus, a 12 h tape can be processed in about 40 min. Processing off-line at many times real time frees the computer for use on other types of processing including searching, on instructions from a data centre, for signals not detected in the initial processing of a digital tape by SASP. In addition, if a SASP breaks down, it is possible, once it has been repaired, to catch up with the back log of recorded data. The disadvantage of off-line processing is that there is a delay between the data being recorded and signals being detected. The advantages of on-line processing are that, not only are signals detected as they are received at the station, but it is possible, at least in principle, for the processor to monitor the performance of the array and indicate breakdowns in the recording system.

2. THE ESKDALEMUIR ARRAY

The EKA array is situated about 20 km north-north-west of Langholm, Dumfriesshire.

The array is roughly L-shaped, each arm of the L having 10 seismometers equally spaced at intervals of about 0.9 km (figure 1). The outputs from the seismometers are recorded continuously in analogue form on 24 channel magnetic tape. The arm of the array running nearest to north-south is referred to as the blue line and the other arm as the red line.

When the EKA array was installed it was assumed that the detection and identification of seismic sources would be done mainly using data recorded at stations within about 20° of the epicentre of the source. Thus, the EKA array was designed to allow an assessment to be made of the value of arrays for improving the signal-to-noise ratio of 1 Hz P waves arriving from distances of less than 20°. One of the main requirements of an array, if it is to be used for signal-to-noise improvement, is that the signal be coherent over the array. In designing EKA it was assumed that, if nothing else, the signal would be coherent over one wavelength. At 1 Hz the maximum wavelength of P waves in the distance range 0° to 20° is about 9 km, hence the choice of 9 km as the length for the arms of the EKA array. However, since the EKA was installed, research on detection and identification of underground explosions has concentrated on the use of signals recorded in the distance range 30° to 90°, usually referred to as the source window; in this distance range the wavelengths range from about 13 to 25 km; thus, EKA is less than half the size that is usually regarded as optimum for recording in the 30° to 90° range. (This is why the YKA, GBA and WRA arrays specifically designed for detection in the source window are about two and a half times the size of EKA.) Nevertheless, the EKA array does provide useful signal-to noise improvement for signals from sources in the 30° to 90° range.

3. ARRAY PROCESSORS AND THE ON-LINE CORRELATOR

The usual way to process signals recorded at an array is to apply time shifts to the output of each seismometer to compensate for the finite time the signal takes to cross the array, sum the time shifted signals, and divide the amplitude of the summed signal by n, the number of seismometers in the array. By this process, usually called the delay-and-sum process (or beam forming), the signal is left unchanged (assuming that the signal is identical at all seismometers) whereas, it is hoped, the noise is reduced at least by $n^{\frac{1}{2}}$.

In general, the further a source is from an array the greater the apparent surface-speed and hence the shorter the time the signal takes to cross the array. For sources close to the array the P waves propagate horizontally with speed α, the P wave speed in the material underlying the array. For a source antipodal to the array the signal propagates vertically upwards beneath the array so that the apparent surface-speed is ∞. For sources at intermediate distances the apparent surface-speed lies between α and ∞.

The maximum time for a wave to cross an array is ℓ/c where c is the apparent surface-speed and ℓ is the distance between the two seismometers with maximum separation. If c is large or ℓ is small, or both, then the time for a signal to cross the array will be so small compared to the period of the signal of interest that simple summing without time shifts will give almost the same signal-to-noise improvement as delay-and-sum processing. The first on-line array processor at EKA - the on-line correlator installed in 1963 (3) - used this simple summing technique. In practice, the correlator could not use the full twenty seismometers in the array because ℓ/c for the full array is too large to get satisfactory results; eight seismometer imputs were therefore used, these eight being those near the intersection of the two arms of the array. The maximum separation between any two of the 8 seismometers is about 3 km so that for a source in the distance range 30° to 90° the maximum value of ℓ/c is about 0.2 s. In general, this is small enough for satisfactory signal-to-noise improvements to be obtained by summing without delays.

The simplest way to process the outputs of an array for which ℓ/c is small is to form and display the straight sum continuously; a seismologist can then pick out by eye possible signals on the summed output, which should show signals with better signal-to-noise ratio than a single seismometer output. However, it is more convenient to use a signal detector to pick out possible signals and edit these on to a chart or secondary tape (or both) for further analysis, thus cutting down the amount of data a seismologist has to scan and allowing detailed analysis to be concentrated on the detected signals. The on-line correlator was designed to be a detector and editor. For the detector the 8 seismometer outputs are split into two groups of four; each group is then summed separately and these partial sums are multiplied together point by point. The product is always positive if the two partial sums are identical, that is, for coherent signals with amplitudes well above the noise, whereas for incoherent noise the product fluctuates about zero. To detect signals the product of the partial sums is smoothed with an exponential window with a time constant of 6 s; for noise with predominant frequencies between 1 to 2 Hz the smoothed output, in general, fluctuates only slowly about zero, but for signals and the occasional burst of coherent noise the output increases rapidly to some peak positive value. A signal is assumed to have been detected when the smoothed output rises above some specified level. Once an apparent signal has been detected the edited output is produced.

Various ways of using the on-line correlator to edit array data were tried at EKA. Originally it was planned that the main use of the on-line correlator would be to produce a secondary tape containing the 20 channels of array output and time for the detected signals only; this secondary tape would then be sent to the data analysis centre at Blacknest for detailed study. (A device was included in the editing mechanism to allow the edited records to start 18 s before the detection time to include a sample of noise (≈ 18 s) ahead of the detected signals.) The on-line correlator with secondary tape was tried at EKA and worked satisfactorily. However, as there was no requirement for routine processing of all detections the secondary tape was little used. The main use made of the on-line correlator was to trigger a high-speed chart-recorder (5 mm/s) that displayed, among other things, the sum of the 8 input channels and the outputs of three single seismometers: one seismometer near the crossover point of the array, and one near the northern tip of the blue line and one near the eastern tip of the red line. The differences between the arrival time of the signal at the crossover and at the array tips could then be used to obtain an estimate of the apparent surface-speed and the azimuth of the signal. From the apparent surface-speed it is possible to estimate a rough distance to a source (assuming the focal depth is negligible) using the empirical relationship between distance and apparent surface-speed (figure 2) at least out to about 90°. With distance and azimuth an estimate of the epicentre can then be obtained. Thus, the epicentre could be estimated by the station staff who also made the basic seismological observations of arrival time, amplitude and period from the charts and so obtained some benefit from the fact that EKA is an array station. In addition, the on-line correlator was used to trigger, via a telephone line, a recorder at AWRE (about 500 km south of EKA) and the sum of 8 seismometer outputs and the output of the seismometers at the array tips were transmitted directly to AWRE.

The main drawback to the on-line correlator was that it could only make use of the outputs of closely-spaced seismometers so that only 8 of the 20 array outputs of EKA could be routinely used. It was therefore decided to replace the correlator with a processor (an OSAP) built around a digital mini-computer.

4. THE DESIGN AND DEVELOPMENT OF THE OSAP

In drawing up the specification for the OSAP it was decided that it should as a minimum carry out the functions of the on-line correlator which it was to replace; that is it should operate on-line, detect signals, and display these on a chart both at the station and via a telephone line at AWRE. The main advantage of the OSAP over the on-line correlator, it was hoped, would be that in summing the array, the OSAP would be able to apply time shifts to the outputs of the seismometers to compensate for the time that signals take to cross the array and produce delay-and-sum outputs using all 20 elements of the array. In addition, it was specified that OSAP should be able to estimate automatically a rough epicentre for the source of detected signals.

For any given velocity (apparent surface-speed and azimuth) it is possible to compute the time differences (delays, sometimes called phasing conditions) between the arrival of a signal at each seismometer of the array. As the signals arriving at the array have initially unknown velocity, the OSAP would have to form continuously beams (delay-and-sum outputs) for a range of delays equivalent to velocities chosen to cover the range of interest, say, speeds of ~ 10 km/s to ∞ from any azimuth. These beams would then be scanned by machine for possible signals and when such were detected the velocity for the beam with the largest amplitude would be taken as the velocity of the signal. As, in general, each velocity can be related to an epicentre on the earth's surface, a rough epicentre for the source of each detected signal could thus be determined.

In order to form beams rapidly it was decided to make use of the procedures used in a SASP (2) in which beams, called line beams, would be formed for each of the two lines of seismometers separately. These line beams would then be combined later to form the total sum. Consider now data from a line of seismometers spaced at equal intervals. Let a_{ij} represent the amplitude of the output from the i^{th} seismometer in the line at time $t = j\Delta t$, where Δt is the sampling interval. Suppose now line beams are to be formed with channel 1 as the time reference and for apparent surface-speeds along the line that produce time differences between pairs of seismometers that are integer multiples of the sampling interval; the time difference between channel 1 and any other channel i will then be $m(i - 1)\Delta t$ where m is an integer. Now the distance between seismometer 1 and seismometer i is $d(i - 1)$ where d is the distance between adjacent seismometers, so the sum at time t

$$s_j = \sum_{i=1}^{n} a_{i,k+j},$$

where $k = m(i - 1)$ will thus bring into phase, signals with apparent speeds along the line of seismometers of $d/(m\Delta t)$. As the spacing of seismometers at EKA is 0.9 km and $\Delta t = 0.05$ s, then to cover the required range of apparent speeds requires $m = 0, \pm 1, \pm 2$, that is 5 line beams are required for each line; this is about half the line beams required for a SASP.

Because of the requirement for fewer beams compared to a SASP, a central processor could be used which was slower, had fewer registers and hence was cheaper than the PDP11 used in the SASPs. On this basis the LSI-2 of Computer Automation Inc was selected as being one of the best models available at the time for the job. Apart from the slower speed and smaller number of registers, computers of the LSI-2 type also differ from PDP11s in that they did not have, at the time OSAP was being made, a comprehensive operating system for program development nor the type of file management facilities required for unattended operation, but, as initially, there were no plans for the OSAP to make use of file orientated peripherals, this shortcoming was not seen as a major drawback to the LSI-2.

Two versions of the OSAP were developed: the first was a single-task processor which took in the 20 channels of array data, detected signals and produced a rough estimate of the epicentre of the source of the signals and an output of the best beam. The single-task processor was tested in early 1978 and was shown to operate satisfactorily provided that the data were relatively free from errors. However, as with other processors the presence of spikes on any channel of the input data tended to produce false detections. Now, false detections due to the presence of spikes can be reduced by using non-linear detectors and particularly the log detector algorithm of Weichert (4). The only drawback to these types of detectors is that they are slower than linear detectors. However, as the work on the single-task processor had shown that the linear detector took up only a small part of the available time, it appeared that there would be sufficient time to use a log detector and, in addition, carry out other tasks such as the editing of detected signals on to a floppy disc. A multi-task processor was therefore developed; this processor was completed in 1979 and began operating continuously at EKA in February 1980. In the remainder of this report we concentrate on the multi-task processor.

4.1 Outline of processing method

The inter-relationship of the various units that comprise the OSAP is shown in figure 3. (Specifications of the main hardware units are given in appendix A.) The analogue signals from the 20 seismometers of the array are fed in frequency modulated form into a special purpose analogue to digital converter (FMDC). The FMDC was designed and built at Blacknest and converts signals directly from frequency modulated to digital form without the need for demodulation (5). The digital signals then pass to the central processor which has a 32K store of 16 bit words. The transfer of the digital signals to the central processor is synchronised by coded time signals fed directly to the processor by the station clock.

Processing proceeds using methods similar to those used by Key et al. (2) in SASPs. The array data are duplicated in the core store, each sample of data being read into two adjacent parts of the core store, these parts being referred to collectively by Key et al. (2) as dual buffers. The advantage of dual buffers in carrying out beam forming is discussed by Key et al. (2). Each channel of data is then read from the dual buffers and filtered by a simple digital filter with binary weights and a pass band of 1 to 2 Hz. The filtered data are now converted to an approximation of the logarithm (base 2) of the filtered data; being a binary base, the process of taking logs can be made rapid. Each input value is reduced to 8 bits, a 4 bit exponent and 4 bit "mantissa". For all absolute values of less than unity the log is set to zero. In taking the logarithm, the sign of the input value is ignored, the sign being assigned to the logarithm itself. The log-filtered data are now stored in a second dual-buffer similar to that holding the unfiltered data.

Detection processing is carried out using the log-filtered data. The result of the log conversion is to make the range of amplitudes of the input data more uniform so signals are detected more by their coherence compared to noise than by an increase in amplitude (see Weichert (4) and Key et al. (2) for further discussion). Line beams are formed for the log-filtered data, 5 beams for each line. Originally the 5 line beams formed were for apparent speeds of $d/(m\Delta t)$, $m = 0, \pm 1, \pm 2$ as discussed above. However, $m = \pm 2$ phases up signals from epicentres at about 20° from the array and, as there is little seismicity in this distance range, it was decided to replace the beam for $m = \pm 2$ with beams with apparent speeds between $d/\Delta t$ and $d/(2\Delta t)$ by using a time difference between channel 1 and channel i of $k\Delta t$, where k is the integer closest to $1.5(i - 1)$. To speed up processing each of the 10 line beams, 5 from each line of the array, is formed only every third sample. The beams are then rectified and smoothed to form a long-term average (LTA) and a short-term average (STA). The STA is a 1.5 s square window of integration of the logarithmic beam amplitudes so, as the beams are formed only every third sample-point, the STA is a sum of 10 samples. The LTA is the output of a 30 s exponential integrator formed by multiplying the old LTA by 0.952 and adding a new STA every 1.5 s. The LTA and STA are now compared and if the STA on the beams for any one of the lines exceeds the LTA by some specified factor a trigger is noted. If both lines trigger within 3 s, a signal is assumed to have been detected. If only one line triggers, then this is noted as a false trigger. The 30 s integrator has an inherent gain of 21 so that the STA has to be divided by this factor before being added to the LTA. This provides a convenient point for adjusting the LTA to STA ratio and thus the trigger threshold.

When a detection has been made the line beams with maximum amplitude are noted. Beams for the red and blue lines are given a code R_1 to R_5 and B_1 to B_5 respectively, so that each detection can be assigned a code (R_I,B_J). Each combination of line beams can be equated to a velocity (apparent surface-speed and azimuth) and hence to the epicentre from which signals arriving at the array would have that velocity. The epicentre is taken as a rough estimate of the epicentre of the source of the detected signal. The distribution of the epicentres for all combinations of line beams is shown in figure 4 and the epicentres are listed in appendix B.

As well as forming beams with the log-filtered data, beams are also formed continuously with the unfiltered data. For each detected signal the semi-sums are formed, the semi-sums being the line beams formed from the unfiltered data corresponding to those line beams that gave the largest amplitudes using the log filtered data. The semi-sums are then added together (with the correct time shifts) to form the best beam (total sum).

The principal output of the OSAP is a total sum. When no signal is present this sum is the straight sum of the outputs of all the seismometers of the array ("infinite velocity" beam). When a signal is detected the best beam delayed to give 30 s of noise preceding the signal is displayed on a chart recorder, the beam code (R_I,B_J) being present in binary form at the beginning of the noise segment. The best beam is played out for 2 min ($\frac{1}{2}$ min of noise, $1\frac{1}{2}$ min of signal) after which the output reverts to the infinite velocity beam, the switch to this beam being indicated on the output by the appropriate beam code (R_3,B_3). Time is indicated on the infinite velocity beam by time pulses at intervals of 5 min. Currently the output is being written via a digital to analogue converter on to a chart recorder (Helicorder - see appendix A) both at the station itself and via a telephone line at AWRE.

The semi-sums and time data for all detected signals (with 30 s of noise) are also edited on to a floppy disc. A twin floppy disc unit is used so that as one disc fills, change over to the other disc can take place automatically without loss of data. Alteration of processing parameters, such as trigger thresholds and control of the program, is via a keyboard. The status of the processor, error diagnostics and lists of signal parameters (file number, trigger time and beam code) are printed out on a line printer. In addition, if a fault develops on any channel, the channel is switched off-line and a message stating this has been done is printed out. All off-line channels are tested every 20 min to see if the faults have been corrected and if they have, the channel is switched on and a message to this effect is printed out.

4.2 Some details of software

The software is written in mnemonic assembler code and run using a systems program - Real Time Executive (RTX) utility program which carries out tasks in specified order of priority. The use of a higher level language such as FORTRAN is not possible because the required speed of processing could not be obtained with such languages.

Transfer of data to the computer makes use of the computer "interrupt" facilities. A "data ready" signal from the FMDC unit transfers control to a 3-word-data-transfer routine located at the "interrupt" address (allocated to the input/output interface) which suspends the data processing while individual bytes of data are transferred to memory. When the specified number of bytes for a data block have been transferred an "end of block" (EOB) operation is automatically initiated. The purpose of the EOB operation is described later.

The FMDC produces data formatted in 5 s sections, each section consisting of 4012 bytes. The first block of 46 bytes is made up of 6 bytes of time and date information and 40 bytes of array data (1 sample of 2 bytes for each of the 20 seismometers of the array). Then follows 18 blocks of 40 bytes each (each block containing 1 sample from each seismometer). The 5 s section terminates with the transfer of 46 bytes of data comprising 40 bytes of array data plus 1 byte to check synchronisation of the transfer and 5 bytes for station identification. The transfer of each block is initiated by a data ready signal and terminates with an EOB operation. Each block of array data is taken at 0.05 s intervals.

The EOB operation specifies the byte count and buffer address for the next data-transfer operation, updates time and data information, reformats the 40 bytes of array data and loads these data into the dual buffers. The transfer of data to the computer memory, the EOB operation and array processing operations are assigned the highest priorities. These tasks must be completed within 0.05 s for on-line operation to be maintained. Some of the lower priority tasks may require several 0.05 s intervals before they are completed; these tasks will be interrupted by higher priority tasks several times before completion.

To set up the OSAP the program is read in from disc using the computer autoload facilities; the program is stored on disc as a set of binary coded machine instructions which have been produced via the central processor from the original assembler instructions. The program is stored in a non-volatile 16K core memory and is retained by the memory during power failures and so does not have to be reloaded when power is restored.

Processing begins with entry to the program at a point labelled 'SYNC ENTRY'; this part of the program checks the computer memory for read and write errors, assigns data-storage regions, initialises the system parameters, schedules the disc-file-manager task and finally synchronises the start of the input-data-transfer sequence to a 5 s marker. The program is only entered at 'SYNC ENTRY' when either:

(1) the system is initially started,

or (2) power is restored after breakdown,

or (3) a synchronising error is detected in the data-transfer sequence.

Entry to the program at a point labelled 'PROC ENTRY' starts data transfer and the execution of on-line processing.

The file management program controls the transfer of data between the CPU and dual-floppy-disc drive-unit. It was designed for unattended operation. The data recorded on floppy disc for each detection consist of a maximum of 23 records each containing 203 words. The first 3 words of each record contain date and time information which provides a convenient record label; the remaining 200 words are 5 s of the best beam data for the red and blue lines.

For the file manager to operate correctly, discs must be replaced before both are full. A full disc contains files of data from 20 detections. When the CPU receives a request to write a record to the disc the file manager reads the status information from sector 0 of the disc in the drive unit which was last used. Sector 0 contains information on the number of files and records and the start address of the next record. From the value of these parameters the file manager decides which drive unit to use next and whether or not the disc requires a label. The only discs that can be labelled are those which have not been previously used by the system or those which have been through the transcription process at Blacknest. Discs are labelled by writing fresh status information to sector 0. This procedure avoids the possibility of overwriting unprocessed seismic data. A status record read from disc is compared to information held in the computer memory and this determines the sequence of operations carried out by the file manager. If both sets of data are identical, then a new 5 s block of data is written to the disc, starting at the location defined by the next record address After each block of data has been written the status information is updated in the computer memory and a new status record is written to the disc. If the status information is not identical, the file manager reads status information from the disc in the other drive unit and repeats the checking procedure. If a match is still not obtained, then the file manager always writes the next file to the disc which contains the maximum number of files. If the number is equal, then drive unit number 0 is chosen. A file which was open when a power failure occurred is closed automatically when power is restored to reduce the loss of data. Files are closed by writing a 64 word directory to the sector corresponding to the file number used. The directory contains: the maximum line beam (log) amplitudes (STA) for each channel in a 3.5 s time interval starting at the trigger time; the code for the best beam; the number of false triggers since the last detection; and the trigger level.

5. PERFORMANCE

An OSAP was installed at EKA in February 1980 and has since operated satisfactorily. Some modifications have been made since installation, principally in the data printed out. An example of the best beam output with beam code for one detection is shown in figure 5. The number of signals detected per year is about 1100 which is similar to the number detected by the correlator. Figure 6 shows a plot of log N against log A for signals detected by the OSAP; N is the number of detected signals with amplitude greater than or equal to A (A is in nanometres). Also shown in figure 6 is a plot of log N against log A for signals large enough for their amplitudes to be measured by an analyst on a single channel visual record.

Assuming that the period of most of the detected signals is about 1 s and that the distance correction factor to convert to body wave magnitude is 3.8 for P signals recorded in the distance range 30° to 90°, the 50% interval probability detection threshold for OSAP is m_b 4.8; for the analyst the threshold is m_b 5.1.

The trigger threshold of the OSAP can be adjusted as required but experience shows that choosing a setting to detect only signals with signal-to-noise ratio of 2 or greater is about optimum. With a higher threshold true signals are missed, whereas with a lower threshold many of the detections are spurious. To obtain an estimate of the number of false detections made by the OSAP at EKA a detailed analysis was made of all the 102 detections that occurred over the period 1 May to 2 June 1980. The onset times and rough epicentres estimated for these detections were compared with the lists of earthquakes from the US National Earthquake Information Service (NEIS) and the Norwegian Seismic Array (NORSAR). Out of the 102 detections 83 were associated with known epicentres, visual examination of the best beam seismogram for the remaining 19 detections showed that 11 appeared to be genuine, 4 were due to bursts of electrical noise and 4 to seismic noise. Thus, for this sample over 90% of the detections appear to be true signals.

Figures 7 to 10 show the results of off-line processing (at the Blacknest data centre) of four signals detected and edited on to floppy disc by the OSAP at EKA. The off-line processor reads in from the floppy disc the semi-sums for each detection and forms and displays (together with a time trace):-

(a) The best beam - the sum of the semi-sums.

(b) The best beam filtered in a 1 to 2 Hz pass band.

(c) The product of the two semi-sums after filtering each with a 1 to 2 Hz band pass filter.

Figure 11 shows the maximum of the STAs for each line beam as a function of slowness for two detected signals. Note that, although the maximum of the STAs does show a clear peak for each line, the peak is rather broad, emphasising again that the OSAP can only estimate the epicentre of a signal within broad limits.

6. CONCLUSIONS

The main conclusion of this work is that is is possible to build a satisfactory on-line processor for use at a seismometer array of the EKA type using a cheap and relatively unsophisticated mini-computer. As with other array processors this study confirms that to avoid a large number of false detections it is advisable to use a non-linear detector rather than a linear detector. The non-linear detector used here is the log detector of Weichert (4). The main disadvantage of non-linear detectors is that they are slower than linear detectors but despite this the OSAP can carry out all its current tasks in about 25% of the available time. With the remaining processing time available it is possible to further automate the recording and analysis of the data and have the processor, for example:-

(a) Measure automatically the onset time, amplitude and period of the detected signals.

(b) Make measurements of noise statistics at regular intervals.

(c) Monitor the operation of the recording system, calibrate the seismometers and identify faults.

With the above tasks automated, station staff would be freed to concentrate on array maintenance.

From the experience gained here it is clear that with the advances in the speed of mini-computers since the LSI-2 was purchased it should be possible to use a modern mini-computer as the CPU of an on-line processor for a 25 km aperture array. Further, by putting two mini-computers into a processor it should be possible at reasonable cost to carry out both on-line and off-line processing at an array. So if the array data were recorded digitally as well as being fed direct to the on-line component of the processor the advantages of both on-line and off-line operation could be obtained.

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1. D H Weichert and M Henger: "The Canadian Seismic Array Monitor Processing System (CANSAM)". Bull Seis Soc Am, 66,1381-1403 (1976)

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3. W H Hutchins: "A Real Time Seismic Array Data Analyser and Its Associated Event Selector". The Radio and Elec Engin, 31, 293-308 (1966)

4. D H Weichert: "Logarithmic Beam Forming for the Suppression of False Alarms in Seismic Detection". Geophys Res Lett, 2 121-123 (1975)

5. B D Hopkins: "Direct High-Resolution Digitisation of a Frequency-Modulated Carrier". J Phys E Sci Instr, 12, 1027-1028 (1979)

APPENDIX A

SPECIFICATIONS

A1. MINI COMPUTER

Type:	LSI-2 with option card for keyboard and printer. 32K × 16 bit core memory
Manufacturer:	Computer Automation Inc

A2. I/O INTERFACE

Designed by Real Time System and resident in the computer main frame.
Twin analogue outputs (multiplexed outputs under software control).
Single bit output for Vela time code.
Single bit control signal to switch on a remote display.

A3. TELETYPE

Type:	Model 43

A4. CHART RECORDER

Type:	Helicorder RV-301 Amplifier AR 311
Manufacturer:	Teledyne Geotech

A5. FREQUENCY MODULATION - DIGITAL CONVERSION UNIT (FMDC)

Manufacturer:	MOD(PE) Blacknest

A6. TWIN FLOPPY DISC UNIT

Type:	Twin 7 in. drives
Manufacturer:	Computer Automation Inc

APPENDIX B

CO-ORDINATES OF BEAMS PROJECTED ON TO THE EARTH'S SURFACE

Each of the 25 beams formed by an OSAP can be specified by the components of velocity on each of the two arms of the array. The beams can also be specified by:-

(a) Azimuth and slowness (s/km).

(b) Azimuth and apparent surface-speed (km/s).

(c) Azimuth and distance of the projection of the beam on to the earth's surface.

(d) Latitude and longitude of the projection of the beam on to the earth's surface.

The table B1 gives the specification of the 25 OSAP beams for the OSAP at EKA in each of the above ways.

TABLE B1

Blue Line Beam Number												
	0.12	337.0	0.10	348.3	0.08	22.0	0.10	55.7	0.12	67.0	SLOWNESS	AZIMUTH
	8.39	337.0	9.87	348.3	11.86	22.0	9.87	55.7	8.39	67.0	SPEED	AZIMUTH
B_5	14.71	337.0	20.5	348.3	24.8	22.0	20.05	55.7	14.71	67.0	DISTANCE	AZIMUTH
	68.16N	18.5W	74.41N	18.0W	75.42N	35.3E	61.97N	33.7E	58.43N	23.2E	LATITUDE	LONGITUDE
	Iceland region		E Greenland		Barents Sea		European USSR		European USSR			
	0.10	325.7	0.08	337.0	0.06	22.0	0.08	67.0	0.10	78.3	SLOWNESS	AZIMUTH
	9.87	325.7	12.58	337.0	17.79	22.0	12.58	67.0	9.87	78.3	SPEED	AZIMUTH
B_4	20.05	325.7	31.07	337.0	69.20	22.0	31.07	67.0	20.05	78.3	DISTANCE	AZIMUTH
	69.00N	35.6W	77.09N	66.9W	52.07N	142.3E	55.08N	52.6E	54.34N	31.8E	LATITUDE	LONGITUDE
	E Greenland		W Greenland		Sakhalin Is		European USSR		European USSR			
	0.08	292.0	0.06	292.0	0.0	0.0	0.06	112.0	0.08	112.0	SLOWNESS	AZIMUTH
	11.86	292.0	17.79	292.0	999.99	0.0	17.79	112.0	11.86	112.0	SPEED	AZIMUTH
B_3	24.88	292.0	69.20	292.0	999.99	0.0	69.20	112.0	24.88	112.0	DISTANCE	AZIMUTH
	56.75N	48.2W	29.61N	98.7W	999.99	999.9	5.27N	57.3E	41.07N	27.9E	LATITUDE	LONGITUDE
	N Atlantic Ocean		Central Texas		Core Shadow		Carlsberg Ridge		Turkey			
	0.10	258.3	0.08	247.0	0.06	202.0	0.08	157.0	0.10	145.7	SLOWNESS	AZIMUTH
	9.87	258.3	12.58	247.0	17.79	202.0	12.58	157.0	9.87	145.7	SPEED	AZIMUTH
B_2	20.05	258.3	31.07	247.0	69.20	202.0	31.07	157.0	20.05	145.7	DISTANCE	AZIMUTH
	47.18N	32.6W	36.18N	39.1W	11.84S	24.1W	25.71N	9.8E	37.71N	10.9E	LATITUDE	LONGITUDE
	N Atlantic Ridge		N Atlantic Ocean		S Atlantic Ocean		S Algeria		Tunisia			
	0.12	247.0	0.10	235.7	0.08	202.0	0.10	168.3	0.12	157.0	SLOWNESS	AZIMUTH
	8.39	247.0	9.87	235.7	11.86	202.0	9.87	168.3	8.39	157.0	SPEED	AZIMUTH
B_1	14.71	247.0	20.05	235.7	24.88	101.0	20.05	168.3	14.71	157.0	DISTANCE	AZIMUTH
	47.67N	23.4W	41.53N	25.3W	31.61N	13.8W	35.57N	1.7E	41.51N	4.4E	LATITUDE	LONGITUDE
	N Atlantic Ocean		Azores Islands region		Madeira Isles region		Algeria		W Mediterranean Sea			
	R_1		R_2		R_3		R_4		R_5		Red Line Beam Number	

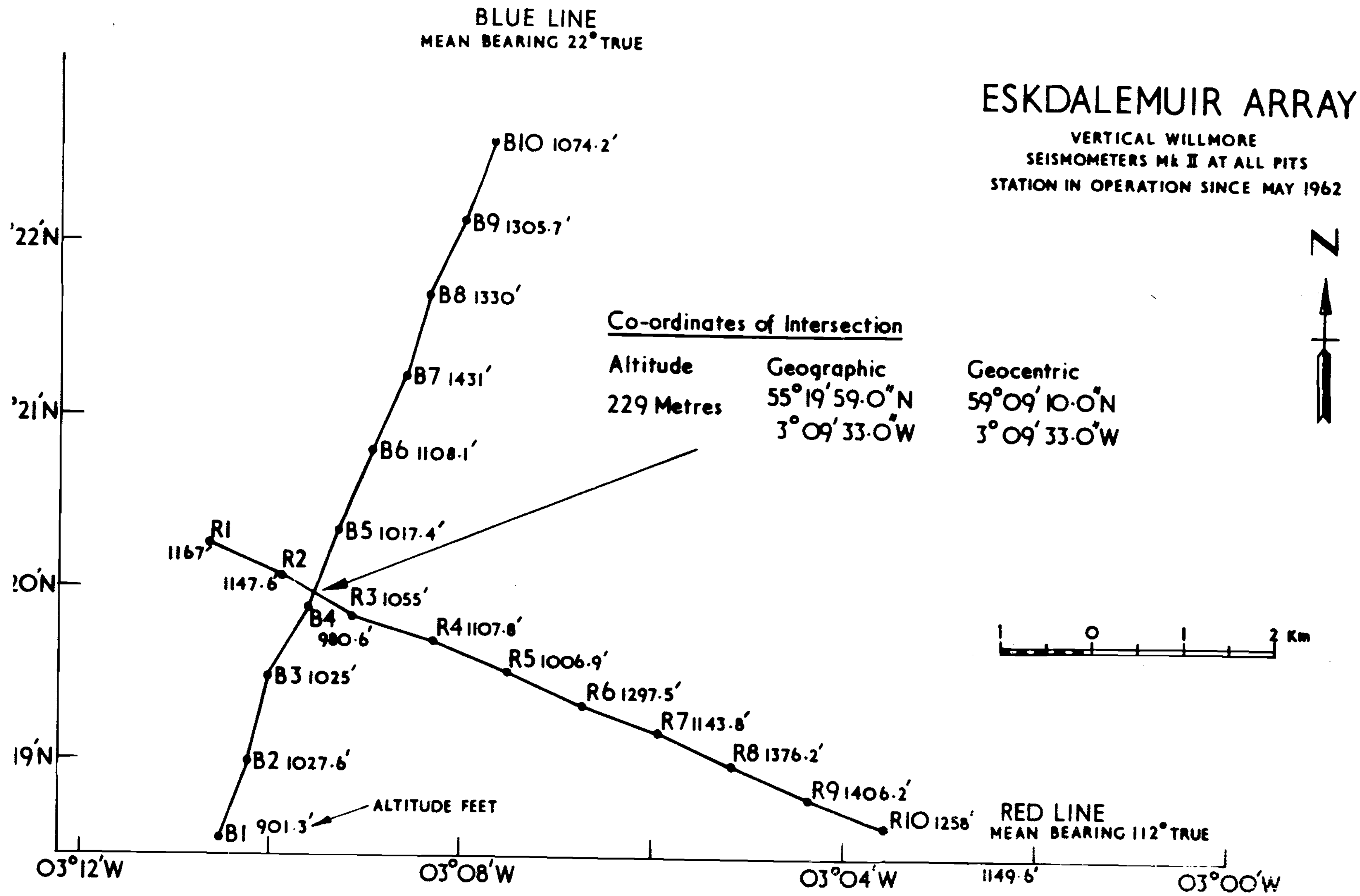

FIGURE 1. Map of the Eskdalemuir Seismometer Array

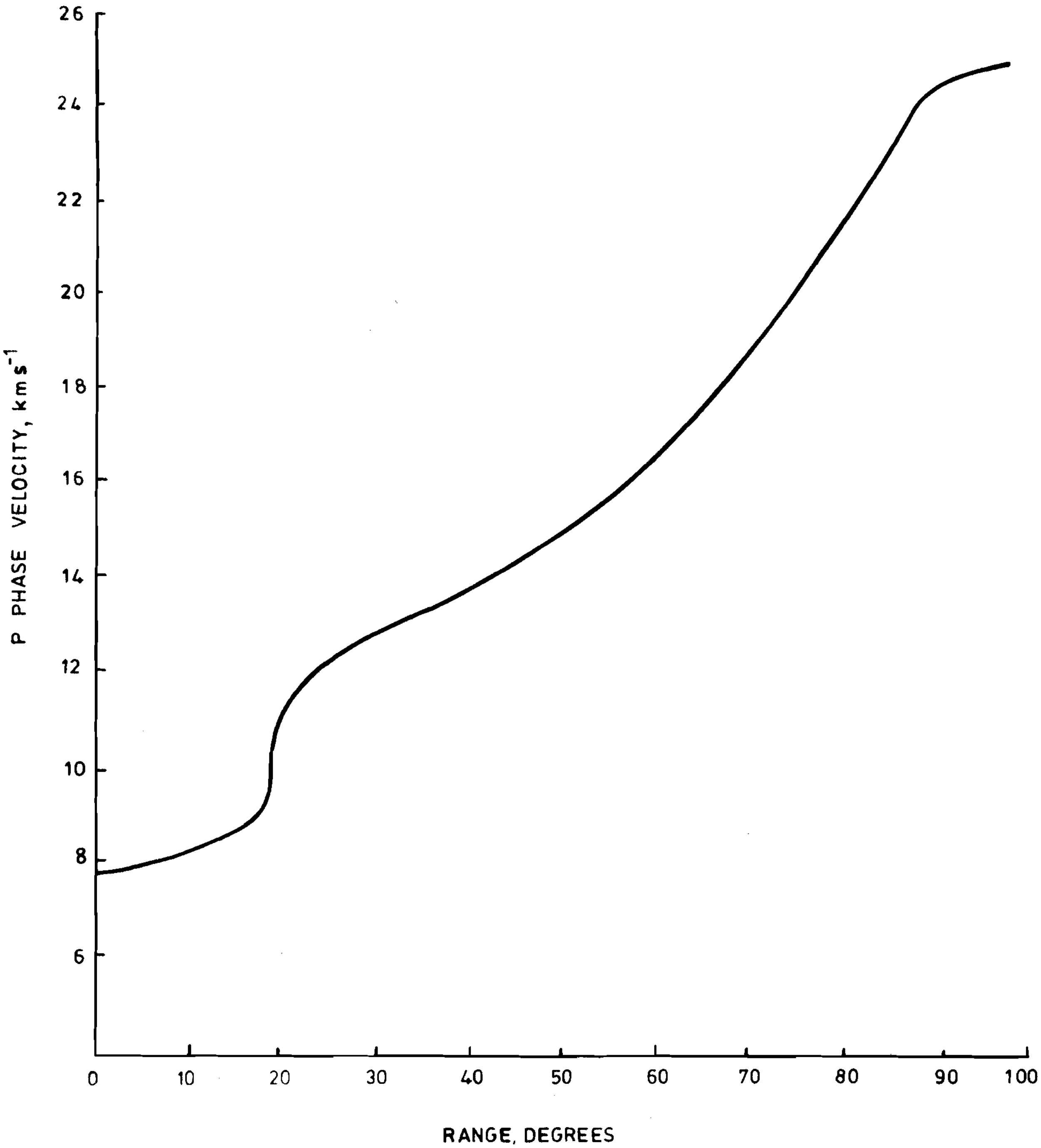

FIGURE 2. Apparent Surface Speed as a Function of Distance

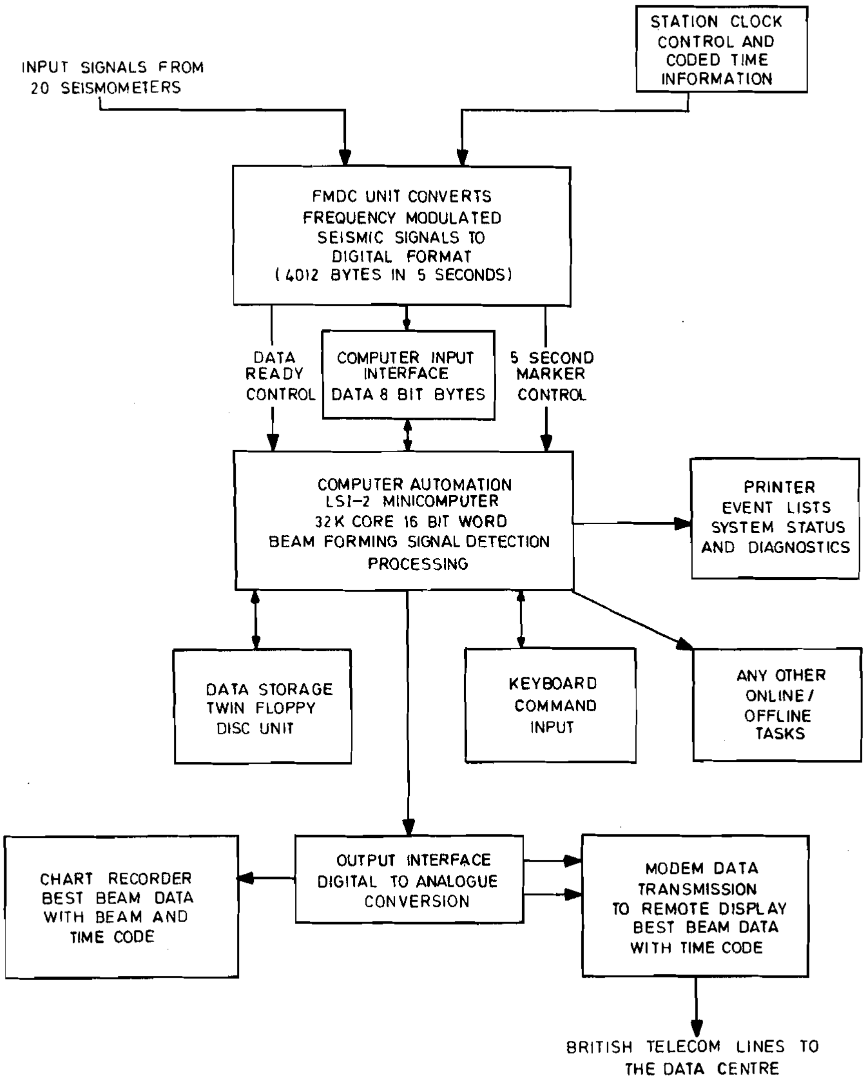

FIGURE 3. Diagram showing inter-relationship of the main components of the On-line Seismometer Array Processor

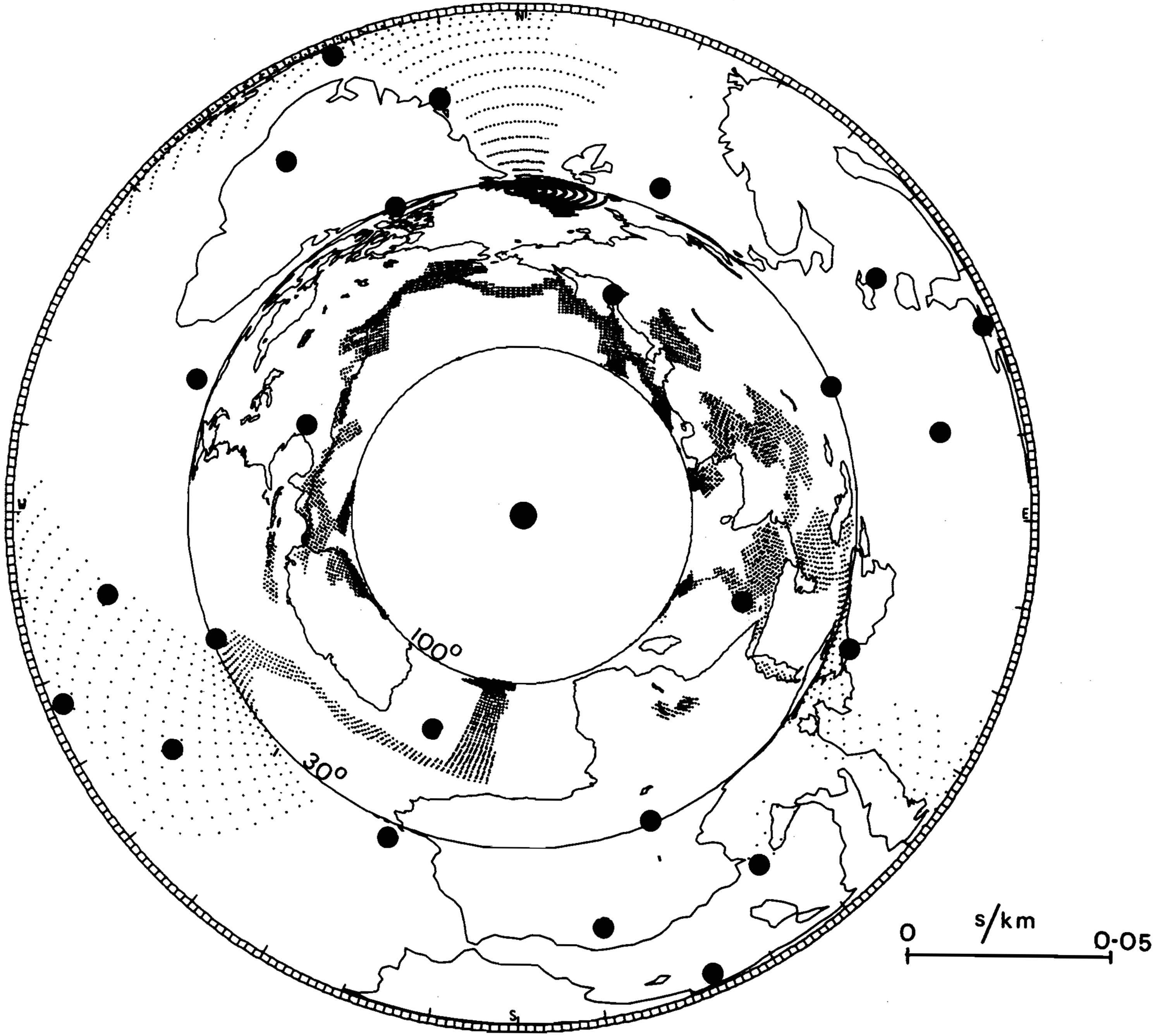

FIGURE 4. Distribution of beam centres in slowness space

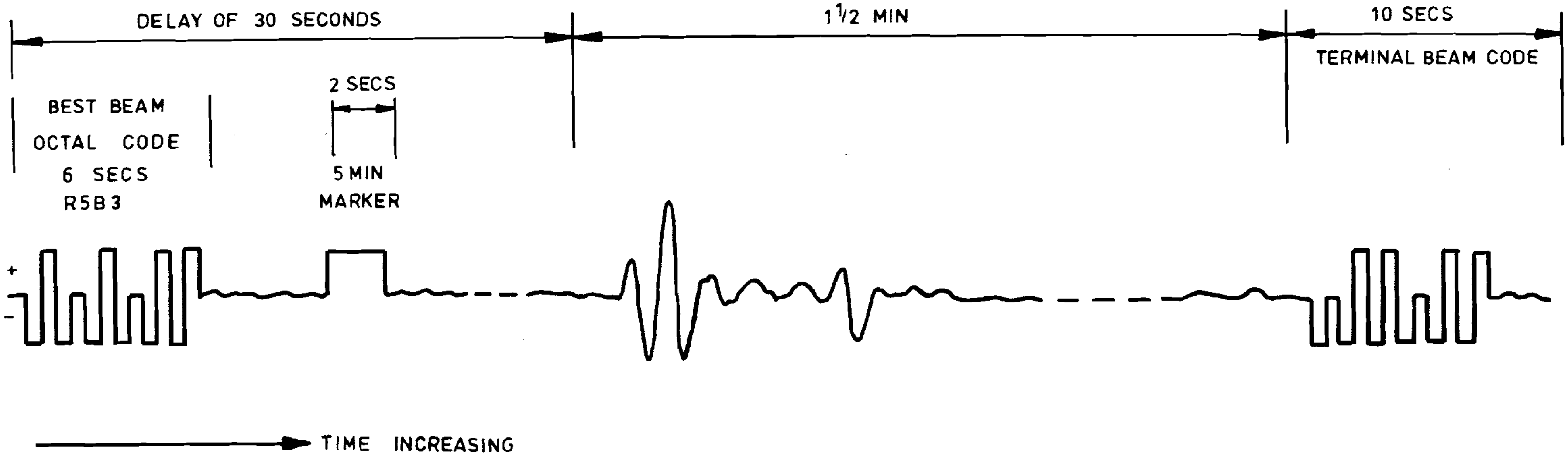

FIGURE 5. Example of Best Beam chart record and beam codes. Best beam code: 0 and positive amplitude correspond to code 0 and 1; negative amplitudes are for bit identification only. The binary code right to left: first 3 code bits for best blue line beam followed by the best red code. Example shows the code for red 5 blue 3.

The terminal beam code $R_3 B_3$ is the code for a display produced by summing all the seismometer outputs with no delay.

The hour markers (not shown) are of 15 s duration.

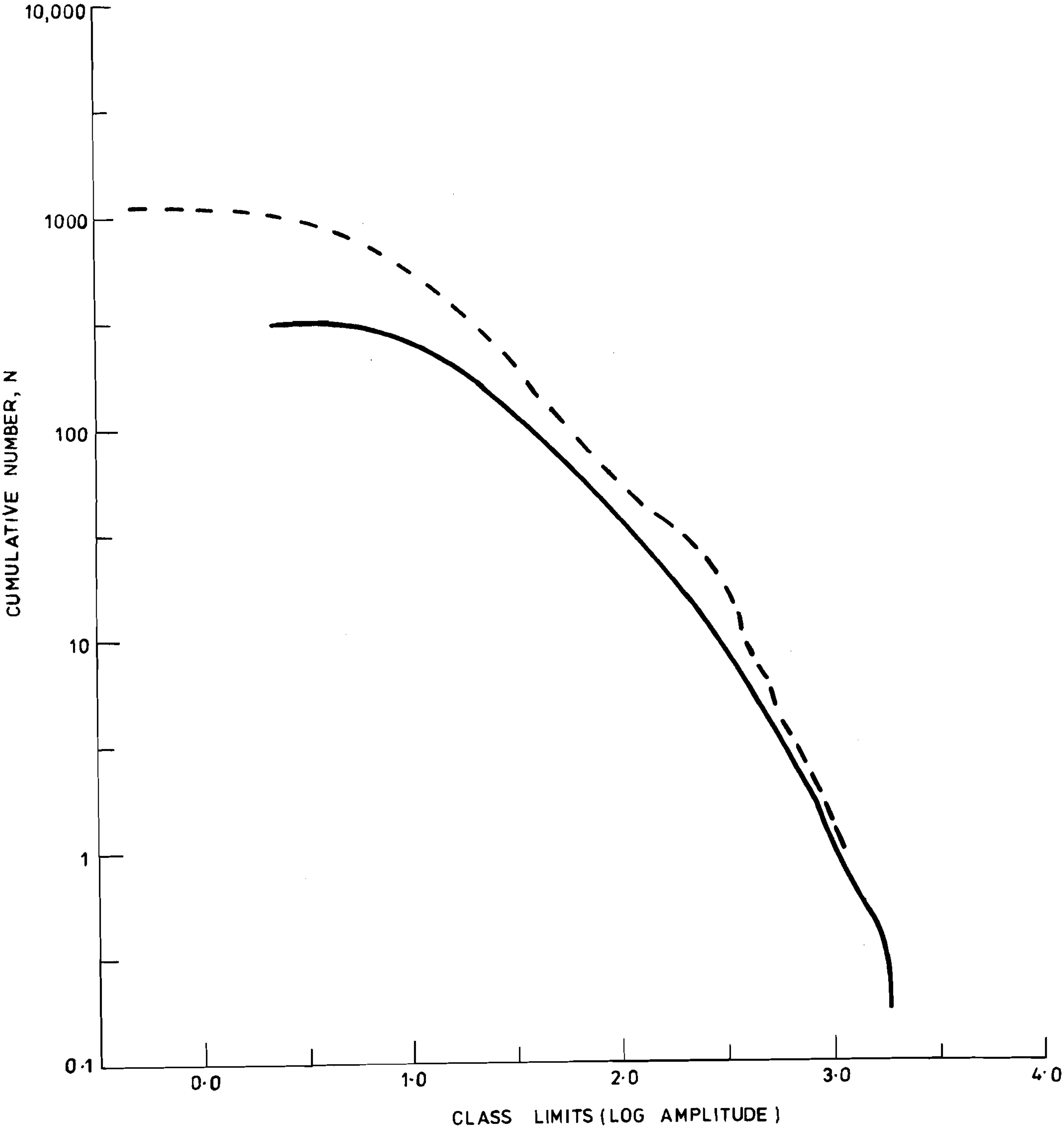

FIGURE 6. $Log_{10}N$ against $log_{10}A$ for signals observed at the Eskdalemuir array. N is cumulative number of detected signals/year with amplitude greater than A. - - Signals detected by the On-line Seismometer Array Processor. — signals observed by analyst on the visual output from a single seismometer (Helicorder)

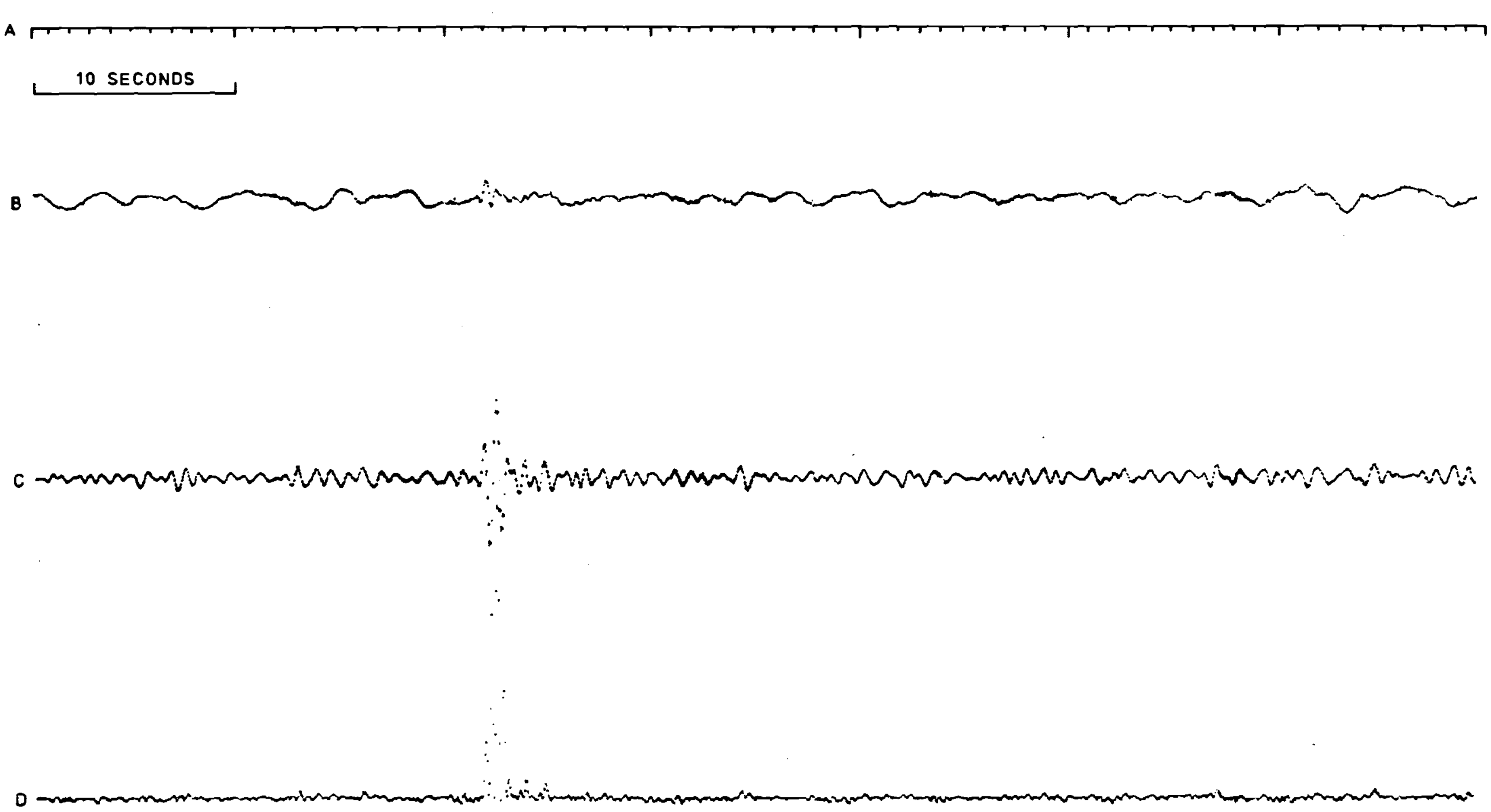

FIGURE 7. Signal detected and edited on to floppy disc by the OSAP at EKA. Trigger time - 14:53:42 on 3 April 1980. Display produced by off-line processing (at Blacknest) of edited records. (a) Time channel; (b) Best Beam (unfiltered); (c) Best Beam (filtered 1 to 2 Hz); (d) Product of two semi-sums after filtering each with 1 to 2 Hz band pass filter.

Signal amplitude on channel (b) is 4.5 nm at 0.6 s period. Beam number is $R_3 B_4$ (Sakhalin Island Region). The signal cannot be associated with any seismic disturbance listed in the reports of the National Earthquake Information Service or the International Seismological Centre. However the Norwegian Seismic Array reports a signal at 14.52.53.6 from a source off the East Coast of Kamchatka so presumably the signal shown here is from the same source

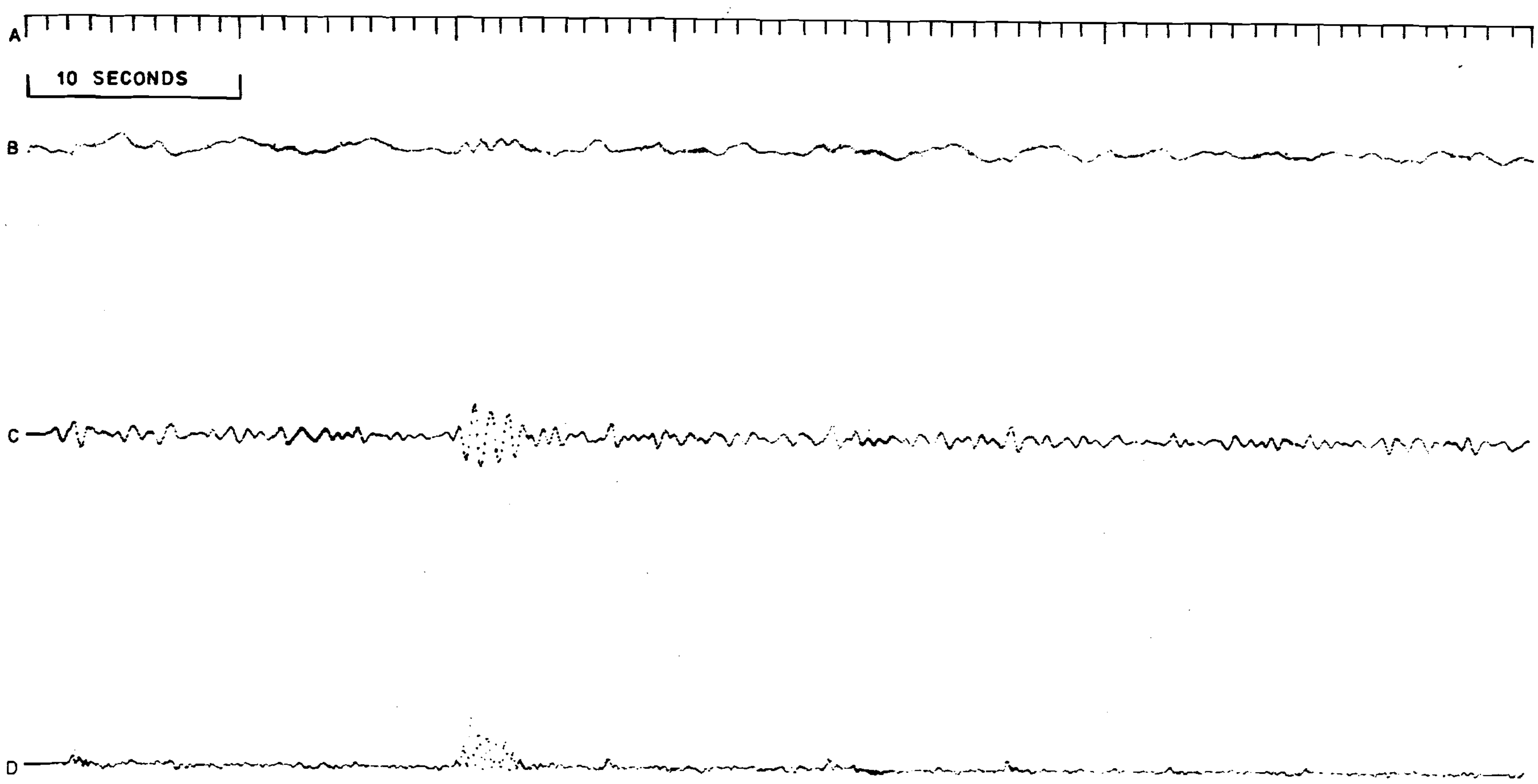

FIGURE 8. Signal detected and edited on to floppy disc by the OSAP at EKA. Trigger time - 17:07:09 on 3 April 1980. Display produced by off-line processing (at Blacknest) of edited records. (a) Time channel; (b) Best Beam (unfiltered); (c) Best Beam (filtered 1 to 2 Hz); (d) product of two semi-sums after filtering each with a 1 to 2 Hz band pass filter.

Signal amplitude on channel (b) is 2.2 nm of 0.6 s period. Beam number is $R_3 B_3$ (Core Shadow). The signal cannot be associated with any seismic disturbance listed in station or data centre bulletins

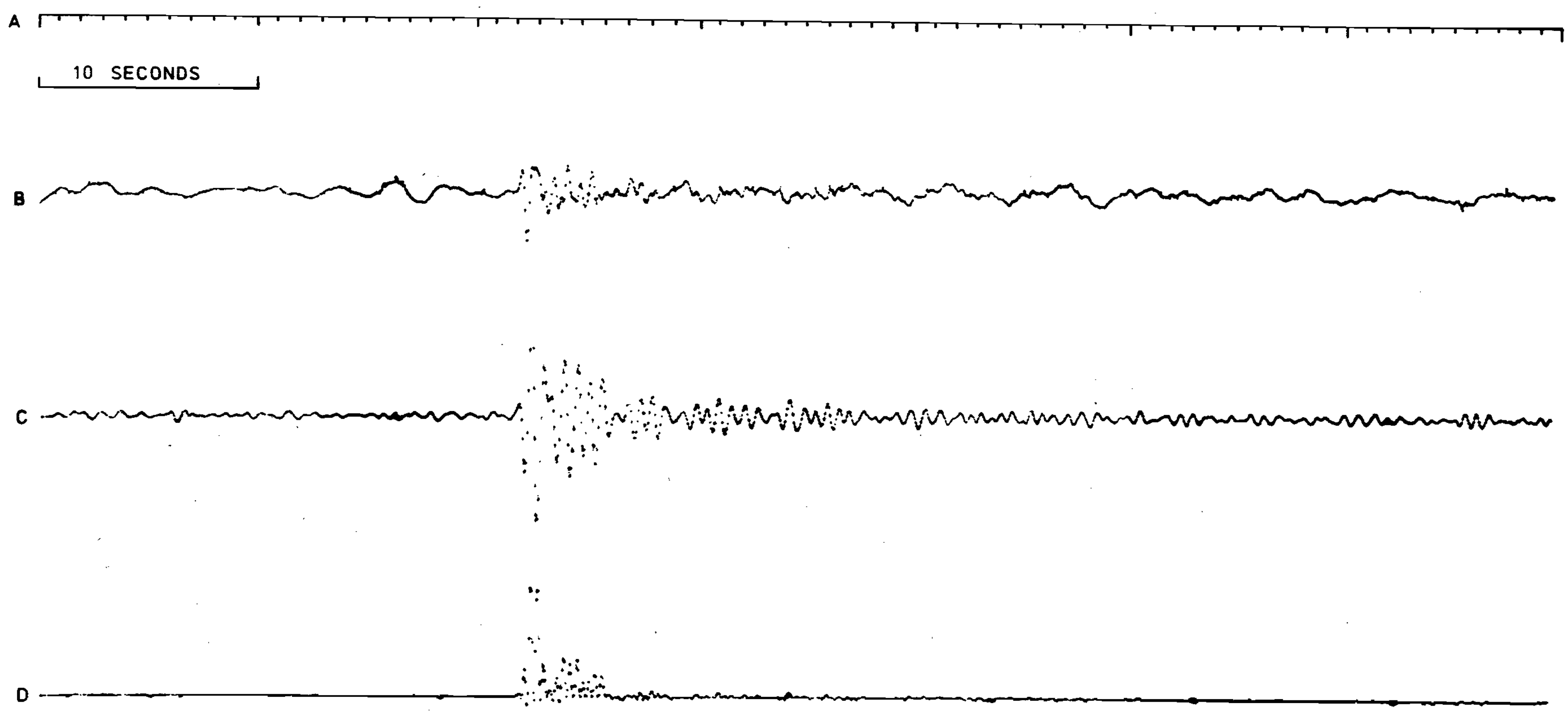

FIGURE 9. Signal detected and edited on to floppy disc by the OSAP at EKA. Trigger time - 04:15:32 on 10 April 1980. Display produced by off-line processing (at Blacknest) of edited records. (a) Time channel; (b) Best Beam (unfiltered); (c) Best Beam (filtered 1 to 2 Hz); (d) Product of two semi-sums after filtering each with a 1 to 2 Hz band-pass filter.

Signal amplitude on channel (b) is 7.4 nm at 0.4 s period. Beam number is R_4B_4 (European USSR).

Comparison with reports of the National Earthquake Information Service show that this signal is from a seismic disturbance (m_b 5.0) in E Kazakhistan (origin time - 04:06:57.6)

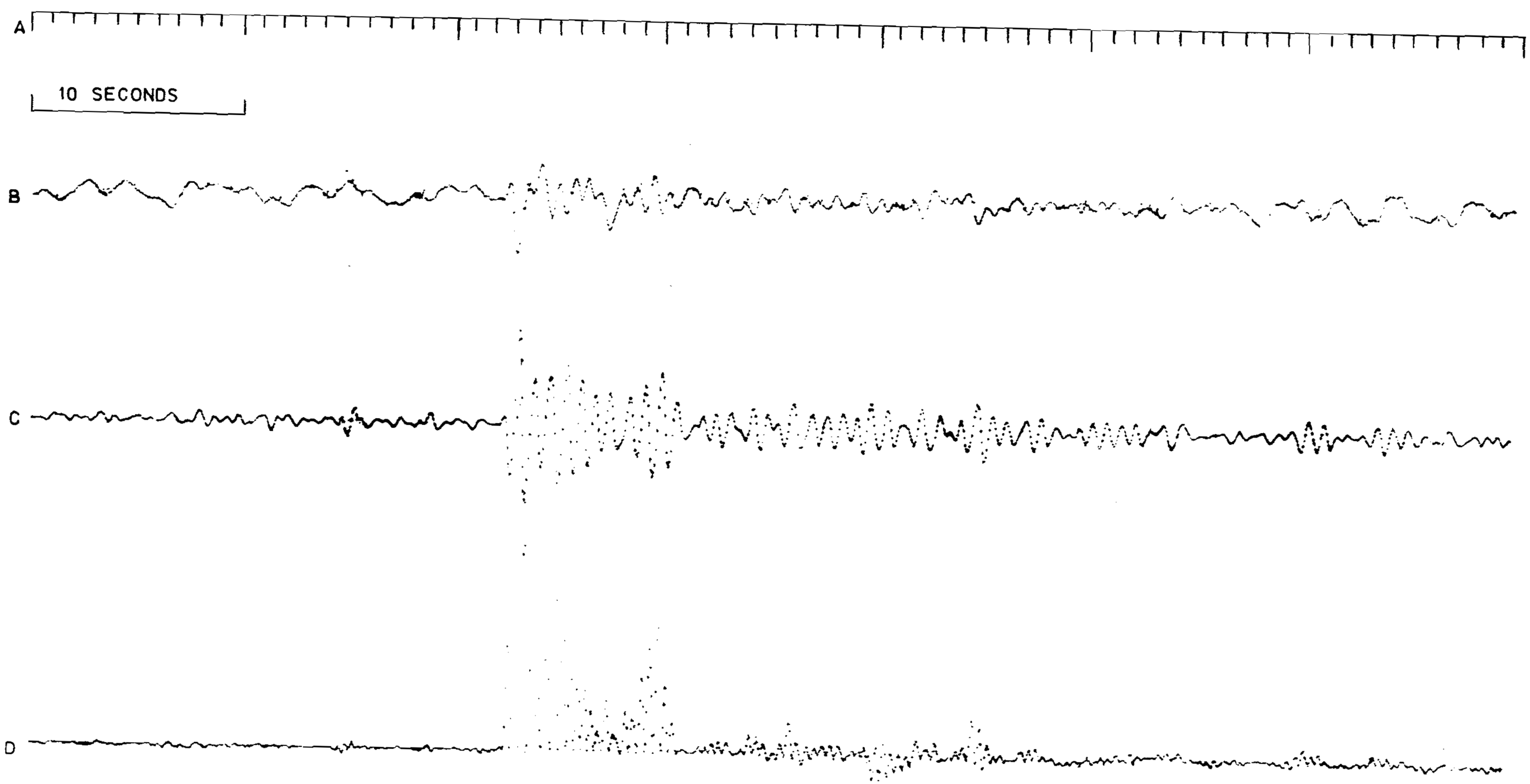

FIGURE 10. Signal detected and edited on to floppy disc by the OSAP at EKA. Trigger time - 20:11:23 on 16 April 1980. Display produced by off-line processing (at Blacknest) of edited records. (a) Time channel; (b) Best Beam (unfiltered); (c) Best Beam (filtered 1 to 2 Hz); (d) Product of two semi-sums after filtering each with a 1 to 2 Hz band-pass filter.

Signal amplitude on channel (b) is 8.7 nm at 0.8 s period. Beam number is R_2B_3 (Central Texas). Comparison with reports of the National Earthquake Information Service show that the signal is from underground explosion (m_b 5.3) at the Nevada Test Site (origin time - 20:00:00.1)

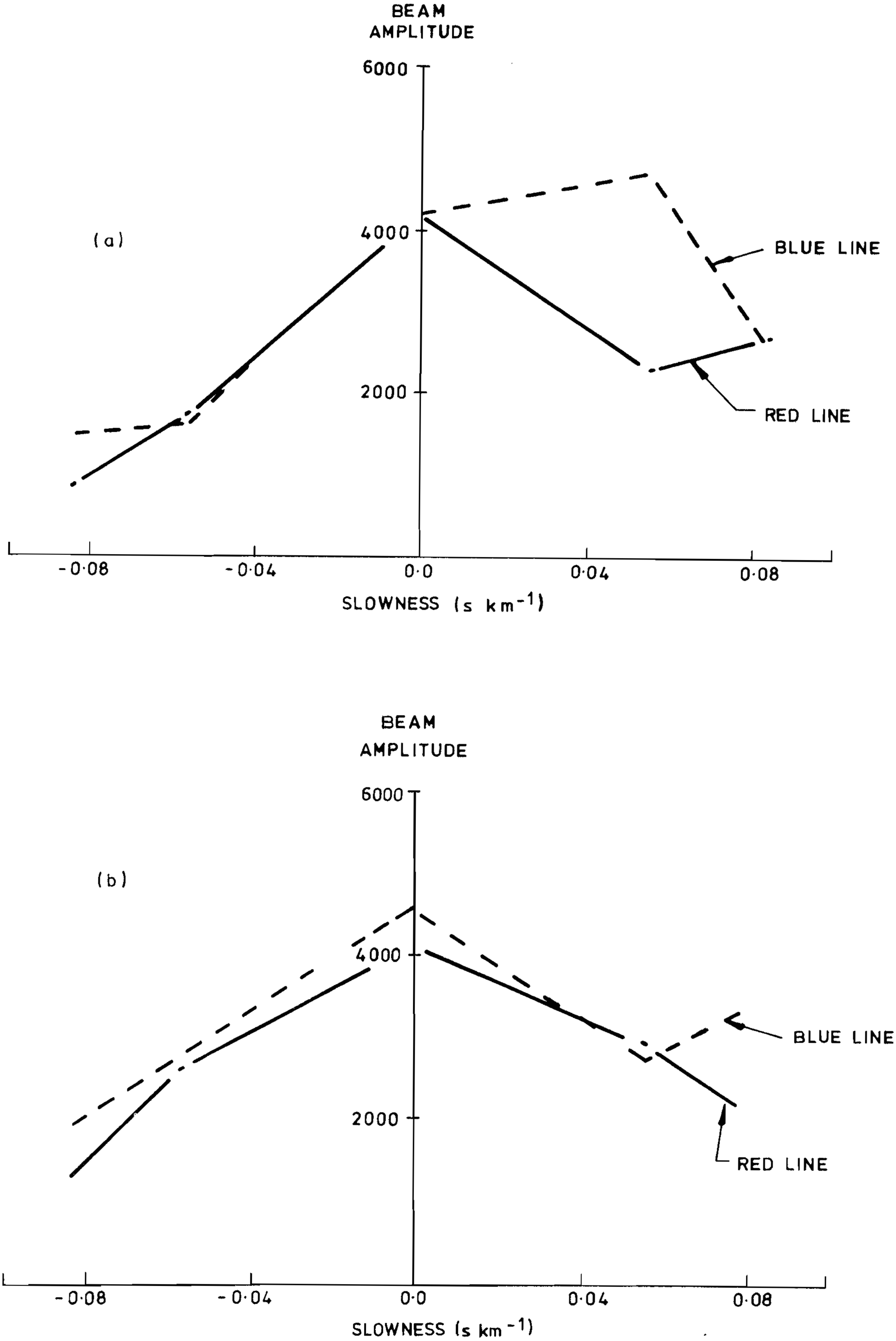

FIGURE 11. Maximum of STA for each line beam as a function of slowness measured in 3.5 s interval starting at trigger time (measured along the array arm) for (a) P signal shown in figure 7; (b) P signal shown in figure 8

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-	Atomic Weapons Research Establishment, Adlermaston, Berkshire
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-	-

7. Title

An On-Line Seismometer Array Processor

7a. Title in Foreign Language (in the case of Translation)

-

7b. Presented at (for Conference Papers). Title, Place and Date of Conference

-

8. Author 1.Surname, Initials	9a. Author 2	9b. Authors 3, 4	10. Date	pp	ref
New S V	-	-	July 1983	28	5
11. Contract Number	**12. Period**	**13. Project**	**14. Other References**		
-	-	-	-		

15. Distribution Statement

No restrictions

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Seismological stations
Seismometer arrays
Digital processors

Abstract The design, development and performance of an On-line Seismometer Array Processor (OSAP) is described. The purpose of an OSAP is to: receive the digitised signals (sampled 20 times per second) from each of 20 seismometers of a 10 km - aperture array of the UK-type; detect seismic signals with a signal-to-noise ratio of about two or greater; estimate the epicentres of the sources of the signals; record the signal data on flexible magnetic (floppy) disc and display the signal information on a chart recorder. The prototype OSAP has a Computer Automation Inc LSI-2 minicomputer as its central processor and has been operating satisfactorily at the Eskdalemuir array, Scotland since February 1980. The log-detector algorithm of Weichert is used in the OSAP as this non-linear algorithm is much better than a linear detector at discriminating between detections due to true signals and those due to data errors, particularly large amplitude excursions of short duration ("spikes"). The experience gained in this study suggests that it should be possible to have almost complete automation of the routine running of an array station of the EKA-type, including: the checking of the system for faults; the calibration of the recording system; and the detection and routine analysis of signals of significant amplitude. At such an automated station the staff would be able to concentrate on array maintenance. It seems possible that a fairly inexpensive processor based on two mini-computers could be developed to run the 25 km aperture UK-type arrays and provide all the facilities available in the currently used off-line processors (SASPs).

Some Metric and SI Unit Conversion Factors

(Based on DEF STAN 00-11/2 "Metric Units for Use by the Ministry of Defence", DS Met 5501 "AWRE Metric Guide" and other British Standards)

Quantity	Unit	Symbol	Conversion
Basic Units			
Length	metre	m	1 m = 3.2808 ft 1 ft = 0.3048 m
Mass	kilogram	kg	1 kg = 2.2046 lb 1 lb = 0.45359237 kg 1 ton = 1016.05 kg
Derived Units			
Force	newton	$N = kg\ m/s^2$	1 N = 0.2248 lbf 1 lbf = 4.44822 N
Work, Energy, Quantity of Heat	joule	J = N m	1 J = 0.737562 ft lbf 1 J = 9.47817×10^{-4} Btu 1 J = 2.38846×10^{-4} kcal 1 ft lbf = 1.35582 J 1 Btu = 1055.06 J 1 kcal = 4186.8 J
Power	watt	W = J/s	1 W = 0.238846 cal/s 1 cal/s = 4.1868 W
Electric Charge	coulomb	C = A s	-
Electric Potential	volt	V = W/A = J/C	-
Electrical Capacitance	farad	F = A s/V = C/V	-
Electric Resistance	ohm	Ω = V/A	-
Conductance	siemen	$S = 1\ \Omega^{-1}$	-
Magnetic Flux	weber	Wb = V s	-
Magnetic Flux Density	tesla	$T = Wb/m^2$	-
Inductance	henry	H = V s/A = Wb/A	-
Complex Derived Units			
Angular Velocity	radian per second	rad/s	1 rad/s = 0.159155 rev/s 1 rev/s = 6.28319 rad/s
Acceleration	metre per square second	m/s^2	1 m/s^2 = 3.28084 ft/s^2 1 ft/s^2 = 0.3048 m/s^2
Angular Acceleration	radian per square second	rad/s^2	-
Pressure	newton per square metre	N/m^2 = Pa	1 N/m^2 = 145.038×10^{-6} lbf/in^2 1 lbf/in^2 = 6.89476×10^3 N/m^2
	bar	bar = 10^5 N/m^2	- 1 in. Hg = 3386.39 N/m^2
Torque	newton metre	N m	1 N m = 0.737562 lbf ft 1 lbf ft = 1.35582 N m
Surface Tension	newton per metre	N/m	1 N/m = 0.0685 lbf/ft 1 lbf/ft = 14.5939 N/m
Dynamic Viscosity	newton second per square metre	$N\ s/m^2$	1 $N\ s/m^2$ = 0.0208854 $lbf\ s/ft^2$ 1 $lbf\ s/ft^2$ = 47.8803 $N\ s/m^2$
Kinematic Viscosity	square metre per second	m^2/s	1 m^2/s = 10.7639 ft^2/s 1 ft^2/s = 0.0929 m^2/s
Thermal Conductivity	watt per metre kelvin	W/m K	-
Odd Units*			
Radioactivity	becquerel	Bq	1 Bq = 2.7027×10^{-11} Ci 1 Ci = 3.700×10^{10} Bq
Absorbed Dose	gray	Gy	1 Gy = 100 rad 1 rad = 0.01 Gy
Dose Equivalent	sievert	Sv	1 Sv = 100 rem 1 rem = 0.01 Sv
Exposure	coulomb per kilogram	C/kg	1 C/kg = 3876 R 1 R = 2.58×10^{-4} C/kg
Rate of Leak (Vacuum Systems)	millibar litre per second	mb l/s	1 mb = 0.750062 torr 1 torr = 1.33322 mb

*These terms are recognised terms within the metric system.