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THE YELLOWKNIFE SEISMOLOGICAL ARRAY

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THE YELLOWKNIFE SEISMOLOGICAL ARRAY

E. B. MANCHEE AND H. SOMERS

ABSTRACT:—The United Kingdom Atomic Energy Authority, in cooperation with the Department of Mines and Technical Surveys of Canada, has established a large seismological array at Yellowknife, Northwest Territories. The purpose of the array is to investigate the possibility that teleseismic detection and identification of underground nuclear tests anywhere in the world may be possible using a relatively small number of similar stations. The Yellowknife Array is a research and development facility, not an operational monitoring station.

Nineteen evenly spaced seismometer vaults are arranged in an asymmetrical cross, each arm of the cross being 22.5 km in length. The output of the single vertical Willmore Mark II seismometer in each vault is recorded on a separate track on magnetic tape. The large size of the array makes azimuth searching and velocity filtering desirable and necessary in the processing of the data. The Department of Mines and Technical Surveys is in the process of acquiring digital computing facilities which will allow the magnetic tapes to be searched for all events at twice real time speeds. In addition to the identification problem, many routine seismological problems may also be investigated by use of this new and powerful tool.

RÉSUMÉ:—La United Kingdom Atomic Energy Authority, coopérant avec le ministère des Mines et des Relevés techniques du Canada, a érigé de vastes installations séismologiques à Yellowknife (T. du N.-O.). Ces installations doivent servir à étudier la possibilité de découvrir et de reconnaître par l'observation des téléséismes les essais nucléaires souterrains faits n'importe où dans le monde à l'aide d'un nombre relativement faible de stations similaires. Il s'agit là, non d'un ensemble de détection, mais de moyens de recherche et de mise au point.

Dix-neuf voûtes séismiques sont régulièrement espacés en forme de croix asymétrique dont chaque bras mesure 22.5 km. Les données provenant de chaque appareil vertical Willmore Mark II dans la voûte sont enregistrées séparément sur bande magnétique. En raison de la grande étendue de l'installation, il est nécessaire et désirable, pour l'enregistrement des données, de déterminer la direction et séparer les ondes de vitesses différentes. Le ministère des Mines et des Relevés techniques possédera sous peu un ordinateur arithmétique qui permettra de rechercher sur la bande magnétique si des événements se sont produits à une vitesse double de son déroulement normal. Outre les recherches d'identification, on pourra à l'aide de ce nouvel instrument élucider plusieurs phénomènes séismiques.

INTRODUCTION

The Atomic Weapons Research Establishment (AWRE), a section of the United Kingdom Atomic Energy Authority (UKAEA), has been engaged in research into the problem of the detection and identification of underground nuclear explosions since 1959. A useful introduction to this subject has been given by Carpenter (1964). The attention of the British scientists has been directed toward the use of a few suitably sited large arrays of seismometers rather than the proposal suggested at the Geneva conference of 1958 of some 180 more or less conventional stations distributed around the world. To enable the large-array concept to be investigated, a number of arrays have been or are being established in various areas of the world. That at Yellowknife is the third and largest of the UKAEA arrays, the others being at Pole Mountain, Wyoming, and Eskdalemuir, Scotland. The Pole Mountain installation was closed down in 1963, but arrays in other more favourable parts of the world are being constructed. The data so collected have been analyzed and studied in England, and improved facilities for this work will shortly be available in both England and Canada. Results to date are very encouraging and the Yellowknife Array Project has played a major role in the development of the concept. It is emphasized that the Yellowknife array is part of a large research and development effort, and is not in any sense an operational monitoring station.

This paper presents an account of the establishment of the Yellowknife array, including a description of physical facilities, a description in general terms of the initial data analysis methods to be used, and a discussion of some of the purely scientific results that may be derived from this installation.

A. PLANNING THE PROJECT

1. Preliminary Negotiations

In April 1962, the British Ministry of Defence approached the Canadian Defence Research Board about the possibility of locating a large seismic array in Canada. There were several reasons for the choice: Canada has a large area of Precambrian rocks, which provide a good base for seismograph stations: it was believed that a seismically quiet area could be found somewhere in the interior of the continent; and Canada could provide sites that would be at the required distance (30° to 90°, see later) from some important earthquake zones and nuclear testing sites. The Department of Mines and Technical Surveys (M&TS) was called in to provide technical advice and at a meeting early in May, 1962, agreement was reached between British and Canadian representatives regarding the form the cooperation should take, subject to Cabinet approval, which was obtained later in May, 1962. In general terms the agreement provided that the U.K. would supply and set up all equipment and train Canadian personnel in its use and that Canada would provide the site, do all construction work necessary, supply all personnel required for continued operation of the array, and join with the British in analysis of the array data. In July 1962, the senior author joined the Seismology Division of the Dominion Observatory, Department of Mines and Technical Surveys, to supervise the Canadian contribution to the joint effort. In November 1962, the junior author was sent to England to become familiar with all theoretical aspects of the British method. He spent one year at Blacknest, Berkshire, the headquarters of the UKAEA group responsible for seismological development, and on his return to Ottawa worked on a method whereby a digital computer could be used to analyze the data recorded by large arrays in the field. This method is described in general terms later in this paper.

2. Preliminary Surveys

In the latter part of July 1962, the senior author accompanied two United Kingdom scientists to Yellowknife to conduct preliminary noise surveys. The Yellowknife area was considered to be first choice because of its location with respect to known nuclear test sites, its remoteness from coastlines and sources of cultural seismic noise, its excellent communications with the outside world, and the fact that it lay within the Canadian (Precambrian) Shield.

The modern town of Yellowknife (population about 3,500) is on the north shore of Great Slave Lake, NWT, 600 miles almost due north of Edmonton, Alta. There is daily airline service to and from Edmonton, a good road link to Edmonton, which is kept open for all but a few weeks of the year, and barge service across Great Slave Lake during the summer. The town was originally built to serve the two major gold mines in the area, Giant Yellowknife and Con Yellowknife, and has now become a centre of northern administration and transport.

Geologically, the area is complex, like much of the Canadian Shield. A strip of ancient volcanics a few miles wide running north-south along the west side of Yellowknife Bay contains the gold deposits of the Giant and Con mines. West of this narrow belt are large granitic areas with little prospect of economic mineralization. To the east of Yellowknife Bay is a large body of highly contorted and metamorphosed sediments with some granitic zones. In this area there are scattered deposits of gold, lithium, tantalum, niobium and beryllium, with traces of other elements. Throughout the entire area there are two major swarms of diabase dykes, one trending north-northeast, the other west-northwest. A large and complex fault system exists to the east and north of the town of Yellowknife, the faults trending mainly north or north-northeast but joining, splitting up and changing direction in an apparently random fashion. Many extensive linears appear in the granitic area west of the town, but these are believed to be part of a joint system or eroded diabase dykes, rather than faults. Virtually nothing is known about local seismicity, but it is believed that the area is stable.

In view of the geology of the area the topography would be expected to be rough, although of low relief. West of Yellowknife the Shield rocks rise abruptly from Great Slave Lake to a height of 25 to 50 feet, then level off in average elevation, rising only a further 100 feet in the next 20 miles to the north of the lake. Within this area, however, granite cliffs of 20 to 40 feet are common, owing to the presence of the joints and eroded dykes already mentioned. The exposed rock is also fairly rough, due to spalling. Rock exposure varies from about 50 per cent to 70 per cent as one proceeds north from Great Slave Lake, the rest of the area consisting of muskeg or small lakes. During the winter months, when muskeg and lakes are frozen, travel is no problem; but during spring break-up and thereafter only a tracked vehicle with its weight well spread can operate efficiently. There are local stands of fairly large trees, but most of the vegetation in the area, apart from the muskeg, consists of low scrub and birch.

Figure 1 shows a portion of the Yellowknife area. Noise tests were carried out at several locations along the Mackenzie Highway as well as on the shores of several of the larger lakes, access to the latter being by chartered float plane. Areas to the east and northeast of Yellowknife were surveyed also, but their remoteness and lack of roads, power and telephone, together with the fact that they were seismically no quieter than the area west of Yellowknife disqualified them from further consideration.

The instrumentation for the noise survey consisted of a Willmore Mark II seismometer and an Ediswan Neocardiograph. The latter consists of a highly portable single-channel (plus time) hot-wire recorder, originally designed, as its name implies, as a cardiograph for bedside use in hospitals. With the addition of a built-in seismic amplifier-filter unit and provision for calibrating both the seismometer and the system, the Neocardiograph becomes a valuable, if temperamental, field instrument. The general method of calibration used has been described by Barr (1964).

During the first two weeks of August 1962, some 15 individual noise traces in various locations near Yellowknife were obtained at various times of the day and night. It was found that the peak-to-peak noise level in the band 1-2 cps was between 1 and 2 millimicrons. This level is characteristic of a good quiet continental site (Birtill and Whiteway, 1965) and since good coupling to well consolidated rock is possible throughout the area the decision was made to construct the array near Yellowknife. Noise checks run subsequently on the full array have indicated that the winter average noise in the 1-3 cps band is in the range 1/2-1 millimicron and the summer average may run as high as 2-6 millimicrons. A comparison between noise levels at Yellowknife and the British array at Eskdalemuir, Scotland, indicates that Yellowknife is quieter by a factor of 10 in the band of interest, although Eskdalemuir is a very quiet site for the British Isles. (Birtill and Whiteway, 1965; Truscott, 1964).

3. Plan for Establishment of the Array

As a result of previous British experience with the Eskdalemuir and Pole Mountain arrays and because of theoretical considerations, the design of the array to

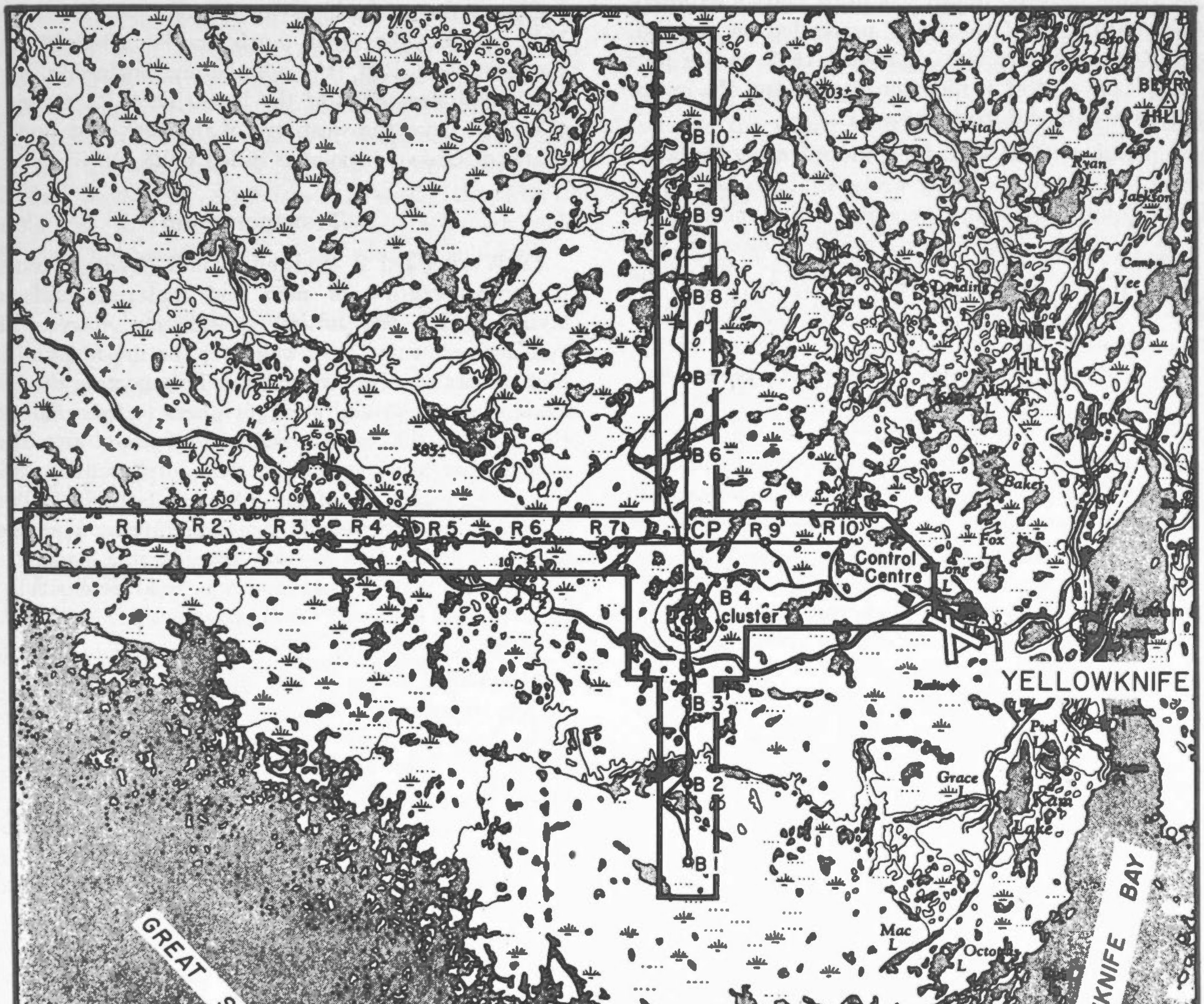

Figure 1. The Yellowknife array, Northwest Territories, Canada. CP is at latitude 62° 29′ 34″ and longitude 114° 36′ 16″

be constructed in Canada had been decided in general terms before the noise survey was begun. The array was planned to consist of two lines of seismometer vaults intersecting at right angles, each line containing 10 vaults plus a common vault at the cross-over point (CP). The separation between vaults was to be 2.5 km, so that each line would be 25 km long. Because of the size of the project and the temporary shortage of some items of equipment it was decided to break establishment of the array into two phases. Phase I covered the completion of all surveying and establishment of 7 operational vaults, 3 on each line plus 1 at CP. Phase II covered the establishment of the remaining vaults. Cable for each phase was to be laid as required. The establishment of the array proceeded as planned, except that each line was shortened to 9 vaults plus one at CP for a total of nineteen vaults, and the entire array was re-cabled during Phase II.

In September, 1962, a Reserve for Scientific Purposes covering the area of the array was granted to M&TS by Order in Council through the cooperation of the Department of Northern Affairs and National Resources. No unauthorized activities may take place within the Reserve, the outline of which is shown on Figure 1.

B. CONSTRUCTION OF THE ARRAY

1. Final Survey

As soon as the Yellowknife site was approved, planning of the array layout commenced. Existing maps and air photographs were examined to find the best way for the arms of the array to run between the areas of muskeg and lakes. Several low-level aerial reconnaissance trips resulted in the final layout shown in Figure 1 being chosen. The arms were oriented exactly north-south and east-west since these directions were as good as any others so far as terrain was concerned and it was thought that some later computations might thereby be facilitated. Survey and construction work was authorized to commence on August 21 and by August 28 a Department of Public Works (DPW) survey party had located the crossover point of the two arms (CP) and had determined true North by means of star shots. This party then began to cut a survey line north from CP, chaining as they went. A second party started on the east-west line.

On September 11 a four-man Army Survey team arrived at Yellowknife to locate precisely the arms of the array with respect to geodetic bench marks in the area. This team ran a 52-mile tellurometer and theodolite loop around the extremities of the north and west arms of the array and also tied into CP and several other positions. Positional closure was 1 in 26,000. Extensive use of a helicopter was made by this crew during its traverse. The crossover point is at an elevation of 668 feet at latitude 62°29′34″N and longitude 114°36′16″W

Vault positions were established along the cut lines by a chaining party attached to the DPW survey crews. Levels were carried from the Yellowknife airport bench mark to each vault location. No vault was finally established more than 200 feet from its surveyed position and the elevation difference between the highest and lowest vault is less than 200 feet. All field surveys for both Phases I and II were completed by November 10, 1962, except for tying in of vaults which were established later.

The vault-numbering system used is standard for all U.K. arrays. The north-south line is called Blue and the east-west Red, the numbering beginning at the south and west ends of the lines. Thus R4 means the 4th vault from the west end of the east-west line. The centre or crossover point is called CP(8,5).

2. Transportation

DPW supplied 2 Nodwell Scouts (tracked vehicles) for transportation of men and materials and cable laying during the initial construction stages. These vehicles performed very well over the muskeg and bare rock areas and were invaluable in transporting the heavy loads of concrete and steel pit liners to the vault locations. After the main construction phase was over a Bombardier Muskeg Tractor was purchased by M&TS for the exclusive use of the Yellowknife project. This is a smaller tracked vehicle useful mainly as a personnel carrier, but also able to carry considerable loads. It has proven very satisfactory and was used extensively for cable-laying during Phase II construction.

A Bell 47G2A helicopter was chartered to ferry men and materials to the more remote vault sites and for getting the various survey parties into and out of the bush. A helicopter was necessary since bulldozers could not go into the muskeg areas to make trail for the DPW Nodwell tracked vehicles until after freeze-up. The Nodwells were used for ferrying supplies and laying cable in the more easily accessible areas near the highway. The helicopter was used from August 29 to October 20, 1962, when it returned to its Calgary base.

After freeze-up a bulldozer was used to clear access trails to all vaults as shown by the thin lines on Figure 1. These trails generally followed the cable runs made by the Nodwells or the surveyors' cut lines. Much of the cable was also laid along these trails from a large sleigh towed by a bulldozer.

During the second phase of construction, when the remaining vaults were brought into operation and all new cable was laid, a second Bombardier Muskeg Tractor was loaned to the project by the Department of Transport (DOT) at Yellowknife. The two Bombardiers carried much of the load during this period although most of the cable laying was done by the bulldozer and sleigh. The Bombardier on loan from DOT was completely reconditioned and returned to DOT in February, 1964, having first been loaned in April, 1963.

The use of the helicopter and Nodwells enabled most of the surveying and Phase I vault construction and cable laying to be completed before freeze-up, 1962. Once the muskeg was frozen it was possible to send a bulldozer in to build proper trails that could be used later by the lighter Bombardiers for construction, cable laying and maintenance.

During various phases of field construction handie-talkies and field telephones were used to maintain communication between the field crews. One tracked vehicle was equipped with two-way radio communication with the control centre, and field telephones were also used for this purpose. A permanent two-way radio link has now been established between the M&TS Bombardier and the control centre, although field telephones are usually used during routine field work.

3. Field Construction

(a) *Vaults*

During the period September to December, 1962, some 13 vaults were emplaced, the remainder being completed during the summer of 1963. Pits were blasted in the solid rock as close to the surveyed positions as possible. Drilling, blasting and mucking out the shattered rock was performed by an experienced hard-rock excavator at an average rate of one complete pit per day. Each pit was approximately 3 feet deep and 5 feet in diameter and care was taken, by firing a series of small charges sequentially, that no shattering of the rock would take place below the bottom of the pit. A few inches of concrete were poured in each pit to level the bottom and to provide a base for the steel pit liners, the actual vaults. These consisted of two steel half-cylinders bolted together to form a vertical cylinder 40 inches in diameter and 20 inches high. A convex lid was bolted on, neoprene gaskets being used at all seams. The bottoms of the vaults were originally set in mastic in a groove in the concrete base but leaks developed, perhaps owing to the extremes of temperature encountered in the Yellowknife area, and most of the vaults were subsequently embedded 2 or 3 inches in fresh concrete. Also, leaks developed in the vertical bolted seams of some of the vaults, so eventually these were welded. A cable entry sealed with mastic was provided near the top of each vault. The pits were backfilled outside the vaults with rubble and covered with sacks of shavings for sound and thermal insulation.

(b) *Cables*

Most field cable was laid from the Nodwells, Bombardiers, or the tractor-drawn sleigh, a rack being built to fit the vehicle in question. Several reels of cable at a time were mounted on the rack and the cable was drawn off by hand and bundled at the side of the trail as the vehicle progressed. During the early fall of 1962, no vehicle could penetrate to the northern part of the array, so cable reels and men were airlifted in by helicopter and the cable was laid by hand. In all cases joining and testing crews followed the cable laying crews.

Originally one six-conductor cable was laid from each vault to the control centre. Each conductor was shielded but the cable as a whole was unarmoured. These cables were supplied in 500-yard reels with bulkhead connectors.

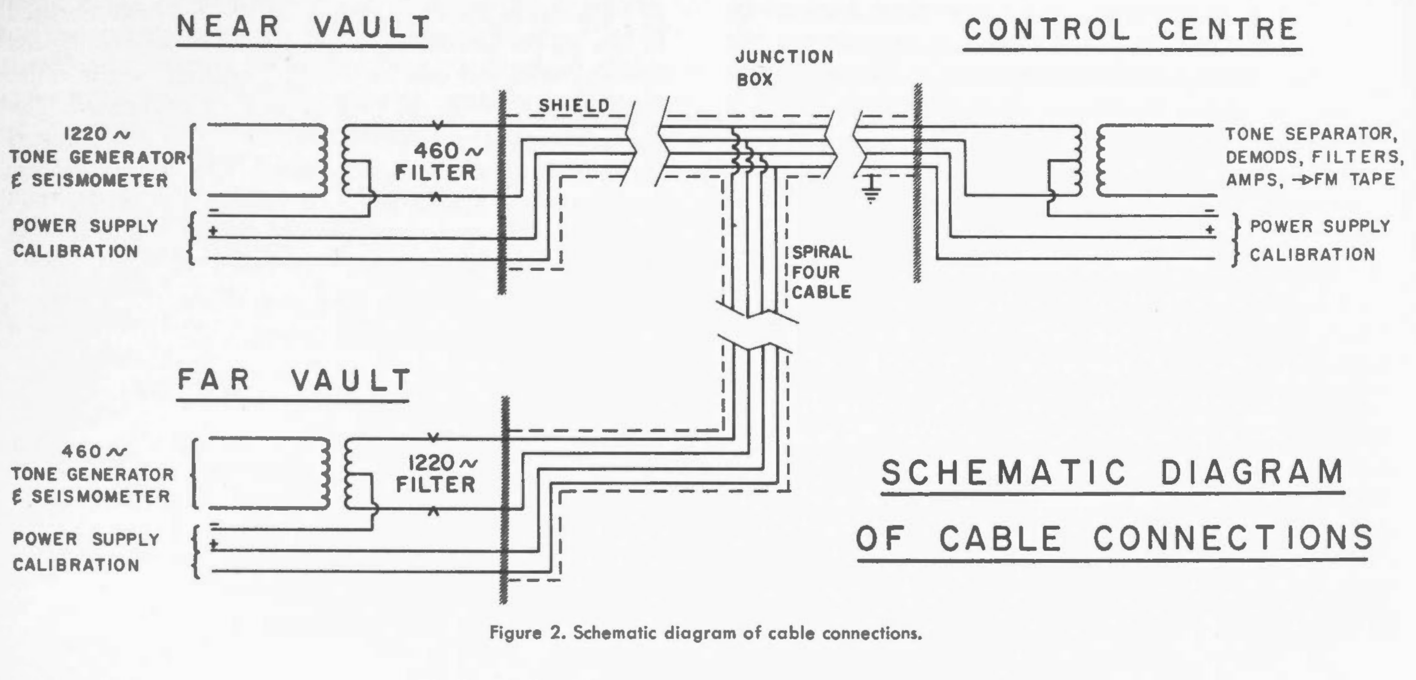

Figure 2. Schematic diagram of cable connections.

The outside covering of PVC proved to be very attractive to rodents and all the cables suffered heavily during the first winter from rodent bites. In some instances the cable was merely stripped of its insulation, in others it was completely severed.

The damage thus inflicted was so extensive and irreparable that it was decided to abandon this type of cable and equip the entire array with a 4-conductor armoured cable known as Spiral Four. This was done during the summer of 1963. The field instrumentation was also redesigned so that one Spiral Four cable could be used for transmission of data and calibration pulses for two adjacent vaults. The Spiral Four was supplied in ¼-mile reels, with heavy clamping connectors. All plugs and sockets in both cable systems were filled with silicone compound before being joined.

Further rodent damage and some extensive damage owing to lightning during the fall and winter of 1963 led to the decision to elevate all the field cables on poles. In the muskeg and bare rock areas it was impossible to set up ordinary telephone poles so 20-foot-high tripods were erected, the cable bundle being laid in the crotch formed at the apex and the individual cables being tensioned every third or fourth tripod. The tripods were nominally 100 feet apart and were guyed to rockbolts or standing timber as required. All connectors were replaced by Scotchcast joints.

(c) *Field Equipment*

Each vault in the array contains one vertical Willmore Mark II seismometer with period set to 1 second and an amplifier-remote calibrator package. The Phase I array used a D.C. head amplifier with data transmission over two of the six conductors in the cable. The other four conductors were used in calibrating. The present system, using Spiral Four cable, is shown schematically in Figure 2. An audio frequency tone is generated in each vault, the vault nearer to the control centre of each pair having the higher frequency. This tone is amplitude-modulated by the ouptut of the seismometer and transmitted to the control centre over one pair of conductors in the Spiral Four cable. Thus the data pair transmits two amplitude-modulated audio frequency signals that must be separated and demodulated at the control centre. The other pair carries the calibration signals. The power for the calibrator stepping relays and the tone generator is supplied as shown in Figure 2.

In addition to the array itself, a cluster of 24 seismometer pits was constructed around vault B4 as shown in Figure 1. The diameter of the solid pattern is 2 km. This cluster was planned as a nontuneable array for obtaining a high signal to noise ratio on seismic events and for use as an on-line editor for signals of interest. The outputs of the seismometers within the cluster may be combined into two groups in a number of ways, and at time of writing experiments are still being conducted. The outputs of the two groups are transmitted to the control centre where further processing may be carried out.

In the cluster, only one tone generator per group is used, and calibration is carried out by groups also. Therefore each seismometer is housed in a small creosoted wooden box, rather than one of the large metal vaults. The boxes were set in pits blasted in the rock, and backfilled and covered in a similar manner to the vaults. All cluster cabling is brought to terminal blocks at the cluster centre, so that great flexibility is possible in the make-up of the two groups. The tone generators are also located at the cluster centre.

4. The Control Centre

(a) *Building*

A prefabricated army hut, 84 feet long by 20 feet wide, was provided by the Canadian Army and flown to Yellowknife by the RCAF in September 1962. It was erected by DPW on a special gravel pad at the location shown in Figure 1 and the interior was divided into rooms as required for the purposes of the array. A large room, 20 feet x 18 feet was set aside at the west end of the building for the laboratory instrumentation. At the east end of the building a large room 28 feet x 20 feet was left for temporary storage and later conversion to a recording room, darkroom and storeroom for one of the conventional Canadian seismic network stations. This station was completed during the fall of 1963 and regular operation started in June, 1964. The space between the two end rooms was divided into a central hall and six rooms. On one side of the hall is the furnace room, living quarters, and storeroom, and on the other side toilet, entrance hall, office, and battery room. Improvements in facilities from time to time have resulted in the development of a fully modern self-contained building with hot and cold running water, septic tank, fluorescent lighting, oil-fired forced-hot-air furnace, telephone, etc. Water is hauled from Yellowknife as required and stored in a 200-gallon tank in the furnace room. Furniture was provided by DPW and M&TS. In 1963 a 6-foot chain link fence topped by barbed wire was erected around the site. Also included within the fence is a 500-gallon gasoline tank and a garage housing a diesel generator for standby power, with space for the Bombardier.

(b) *Power*

Since virtually all the laboratory equipment was provided by the British, the main power supply must be 240 volts at 50 cycles. A 4160-volt, 3-phase, 60-cycle line passes near the building and provides primary 60-cycle power through a pole-mounted transformer. All lights, furnace blower, wall plugs, etc., operate directly from this power. The instrument racks, however, receive their power via the battery room. Two Legg battery chargers operating from the primary 60-cycle line keep a bank of batteries charged to 24 volts. The batteries then drive two transistorized inverters which produce 240 volts at 50 cycles. In case of a power failure the batteries will run the racks for a few hours, but a diesel generator is on standby should longer operation be necessary. The generator produces 240 volts at 50 cycles and hence this power may be fed directly to the racks.

(c) *Laboratory Instrumentation*

(i) *Recording.* The Yellowknife array is concerned only with collecting and storing seismic information, so playback and interpretive instrumentation has been confined to the minimum required for monitoring.

As mentioned previously, each Spiral Four cable carries information from two adjacent vaults. Thus there are at present eleven cables entering the control centre, ten for the array and one for the cluster. After passing through a balancing panel where resistances are inserted to equalize the effects of different cable lengths, etc., the cables enter the racks. Here they are separated according to their function, i.e., power, calibration, or signal. The signals are demodulated, amplified, frequency-modulated and fed to the primary tape deck. The FM centre frequency is 270 cps with a peak deviation of $\pm 33\frac{1}{3}$ per cent. The primary tape deck is an EMI standard TD-6 deck accepting a 7,200-foot reel of 1-inch-wide tape. The tape speed at present is 0.3 in/sec so that more than 3 days' recording may be contained on one reel of tape. Two 12-track staggered heads provide for a total of twenty-four channels to be written on the tape. A pair of replay heads are displaced 5.1 inches along the tape so that information may be played back seventeen seconds after it is recorded. The twenty-four channels are composed of twenty-one signal channels, 2 FM error correction channels (one for each bank of heads), and a coded time channel.

(ii) *Monitoring and calibration.* A 4-channel hot stylus recorder is provided for the purpose of monitoring any 4 selected channels taken from the replay heads. Usually 3 signal channels plus the time channel will be displayed. Thus a visual record may be kept of what calibration information has been put on each tape channel. Also any channel may be checked for noise or improper operation at any time and adjustments in the field may be monitored visually in the laboratory while they are being done, communication between laboratory and field being maintained by two-way radio and field telephone. Furthermore, the 8-pen recorder mentioned in (iii) below may be used to monitor certain areas of the operation.

Calibration may be performed on the array seismometers in groups of two and on each group of the cluster separately. By means of stepping relays in the vaults, which are controlled from the laboratory by the calibration conductors in the Spiral Four, a current is passed through the coil of the seismometer sufficient to lift the mass to its highest position. After a set time delay the current is stopped and the mass drops and begins oscillating at the natural frequency of the system. The oscillatory current thus generated in the coil is recorded on the proper channel on the primary tape, on the Helicorder, and on the 4-channel recorder. This trace, together with the recorded height of calibrating pulses of known voltage that are passed through the system with the seismometer shorted out, enable one to calculate the natural period and velocity sensitivity of the system. A complete calibration of this type is performed each day for every seismometer in the array and cluster, and adjustments in the field are made as required.

The over-all frequency response of the system including seismometer, magnetic tape recording, and tape replay onto a paper recorder, is given in Figure 3, where it is plotted for a constant velocity input. A ground particle velocity of 10^{-5} cm/sec produces a signal of about 1 volt in the pass band. The maximum dynamic range is 52db on the magnetic tape, and average system noise referred to the vault amplifier input is equivalent to a peak ground velocity of 10^{-7} cm/sec within the pass band of the system. For the Helicorder records, a trace deflection of 1 cm corresponds approximately to a ground particle velocity of 16 millimicrons/sec.

(iii) *The Cluster.* The cluster signals, as well as being put on the tape, are used to trigger a secondary recording system when a seismic event is detected. Various methods of combining the cluster signals are available, but one example may suffice. The cluster is divided into two groups of twelve seismometers each and each group is

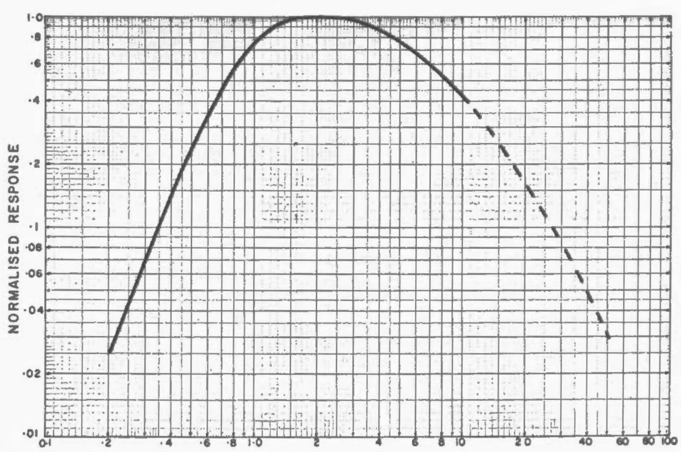

Figure 3. Yellowknife over-all frequency response for constant velocity input.

summed in the field with no phase shift. The two summed signals are then multiplied together in the laboratory and integrated with a short time constant in an analogue correlator. When the integrated output rises above a preset level a signal that is coherent across the dimension of the cluster has been detected. If this occurs, a secondary tape deck is started, which records all twenty-four channels from the primary deck by way of the replay heads. An 8-channel pen recorder is also started, which displays a selection of outputs from the primary tape and correlator. The secondary tape deck and recorder can be set to run for a preset time, say 2 minutes, after a trigger, after which the correlator level is again sampled to see whether a signal is still present or not. As a result of this sampling, a decision is made as to whether the secondary tape deck and recorder should be shut off or continue to run. Thus the secondary tape deck produces an edited tape containing only events that have produced a correlator signal above the preset bias level. The 8-trace recorder provides a record of the event that caused the trigger, together with a few by-product traces.

(iv) *Helicorders.* Two Helicorders complete the roster of laboratory recording devices. These may be made to record the output of any field seismometer or group of the cluster. Their main purpose is to be sure that the entire sensitivity range is covered by visual records; thus one Helicorder is usually run at high sensitivity, the other at low sensitivity.

(v) *Timing.* A local crystal chronometer with a stability of 5 parts in ten million provides 1-second pulses to all the recording apparatus. Wider pulses are provided to mark each 10 seconds, minute, 5 minutes, half-hour and hour. In addition, each minute mark is so coded by following digital pulses that the minute, hour and day may be read immediately. Details of the timing code are given by Truscott (1964). All these special marks, except the half-hour mark, are put on the primary tape and devices operating from the replay heads; only the minute (and half-minute), five-minute, half-hour, and hour marks are put on the Helicorders. In the latter case each hour mark is coded with the hour only. The local clock is checked every day against WWV or CHU and accuracy is maintained within $\pm$ 0.05 sec.

(vi) *General.* The laboratory is well equipped with tools, test equipment, and spare parts, and is operated by two qualified electronics technicians, under a resident station engineer. All personnel live in Yellowknife and drive to the station daily, a distance of 6 miles.

C. PROCESSING METHODS

The theory of large seismological arrays has been discussed in a definitive paper by Birtill and Whiteway (1965), and by Whiteway (1965). Only a brief restatement in general terms is made here before processing methods are described. The above papers cover mathmatical statements concerning correlation methods, azimuth and velocity filtering, and the responses of different array configurations. The literature of radio astronomy, radar, and acoustics also contains much pertinent information on array technology.

The object of seismology is to determine the constitution and internal structure of the earth. An associated objective of the investigations being carried on by the UKAEA is to derive methods for differentiating between explosion-generated and earthquake-generated body waves. To examine the latter problem it is necessary to study in some detail the travel times, relative energy content, and frequency content of all possible phases due to a given event. To do this the various wave packets arriving from the event at a station must be detected, isolated from the ambient noise and other interfering wave-trains, and made available for further analysis. The most powerful method so far developed for achieving these ends is the use of a phased seismometer array with dimensions comparable to the longest wavelength under consideration. Of the many array configurations possible, that of the asymmetrical crossed array was chosen for Yellowknife as providing the best combination of desired theoretical response, accessibility, and utilization of local topography.

The output of each vault (i.e., each seismometer position in the array) is recorded on a separate track on the magnetic tape. Thus it is a relatively simple matter to introduce variable time delays between these outputs. This in turn enables the array to be tuned ("phased") to phases arriving from a particular azimuth with a particular apparent velocity. A discussion of array responses for certain idealised array configurations is given in Birtill and Whiteway (1965), and the velocity and azimuth resolutions of the particular Yellowknife configuration have been published by Somers and Manchee (1965). In the latter paper it is also shown that, of those considered, cross-correlation of two groups of array elements is the most powerful and economical method of signal retrieval. In general, then, the preferred method for treating data from the Yellowknife Array is to introduce time shifts in each channel relative to some point on the array such that energy arriving from a particular azimuth with a particular apparent velocity is in phase on all channels. The channels are then summed into two appropriate groups and the two sums are multiplied together and averaged with a time constant of a few seconds in a correlator. The correlator output will then be a measure of the cross-correlation integral of the incoming signal at any given time and may be plotted against time to provide a sensitive indicator of coherent signal on the array. When the chosen azimuth and velocity are correct for a signal that is sweeping across the array the correlator output will rise sharply to a maximum, then drop off to a value typical of the statistical correlation of random noise. For a signal sweeping across the array with a different azimuth or velocity the combination of time shifts to give a maximum correlator output will be different. At all times the array will discriminate against random noise, coherent microseismic noise, and all unwanted signals, unless they happen to correspond in velocity and azimuth to the signal being sought.

It is apparent that the half-space under the array may be searched in a continuous fashion for signals, if analogue means are used. This in fact was the method first used by the UKAEA scientists in the processing of their array tapes. The signals from an event whose azimuth and distance were known were transcribed onto an endless twenty-four-track tape loop. The signals were then retranscribed over and over again on a much larger tape loop at progressively higher and higher tape speeds. At each speed the signals were taken selectively from the tape by a set of fixed staggered read heads, one head per channel. Thus each speed corresponded to the insertion of a particular delay time between the selected channels, i.e., a search condition. In practice the azimuth of a particular event was determined from other evidence and the playback speeds were so adjusted that the half-space was searched for different P modes in arbitrarily small increments of apparent velocity. The signals were summed, multiplied and smoothed in an analogue computer, and the correlator output produced a wiggly line on one channel of an 8-pen recorder. An example of the output thus obtained when the Yellowknife array was phased to the P-wave arrivals from the French Sahara test of 18th March, 1963, is given in Figure 4.

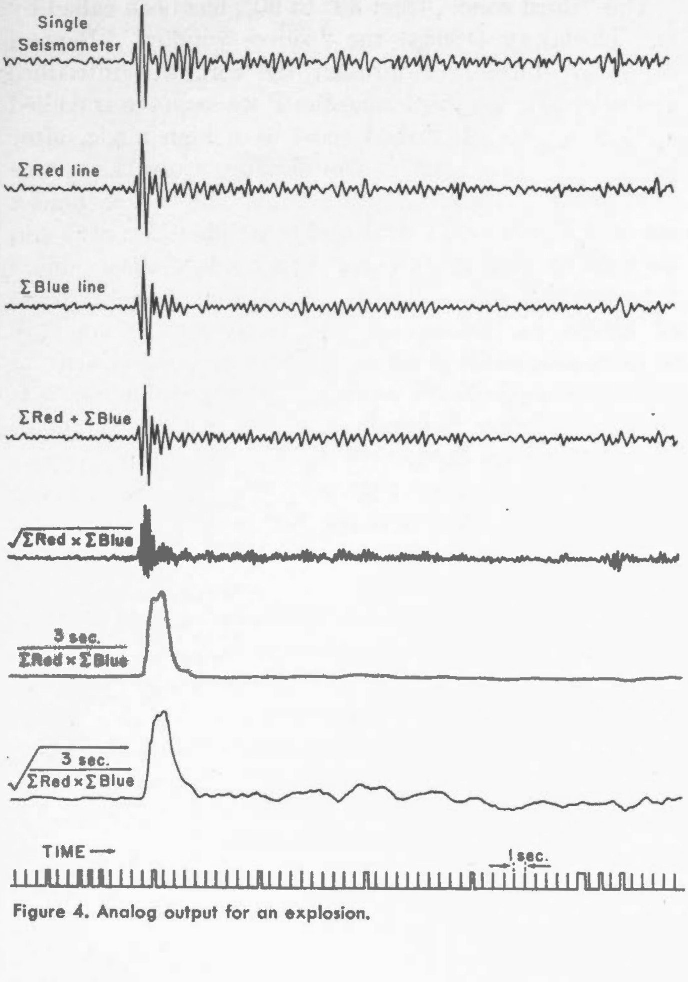

Figure 4. Analog output for an explosion.

The analogue method described above, while able to search the half-space continuously, is very slow. Only a few events can be processed per day. In order to attain high processing speeds, analogue methods must be abandoned and digital methods employed. As soon as the decision has been made to process digitally it must be realized that a continuous search of the half-space is no longer possible, since the data itself will no longer be continuous. By making the sampling rate high enough it would be possible to conduct a virtually continuous search, but the storage requirements in the computer would be vastly expanded and the apparent sensitivity of the search would soon be limited by the inherent accuracy of the field data. Also if it is desired to conduct the initial search and first-order processing in real time or faster, it is necessary to limit the number of search conditions to something the computer and peripheral equipment can handle. For these reasons some compromises must be made in the selection of sampling rate and number of search conditions. Consideration of frequency content, array size and configuration, and overall economy have led us to select twenty samples per second per channel as the sampling rate for first-order processing. Also it was considered that a minimum of 72 search conditions (e.g., 3 velocities at 24 azimuths) should be aimed for. With these requirements in mind M&TS has recently purchased a Model 3100 computer from Computing Devices of Canada Ltd. (CDC). It is expected that the CDC 3100 will allow the Yellowknife field tapes to be searched in approximately 200 search conditions at twice real-time speed (i.e., 24 hours of field data will be processed in 12 hours). After experience has been gained in this mode of operation it is likely that even higher speeds of operation will be attempted. In this event, fewer search conditions will be possible.

The search program is planned to operate as follows: the nineteen signal channels plus the time channel will be amplified, demodulated, and filtered. Band-pass filtering of 1/2–4, 1–2, 1/2–1, 2–4 cps will be possible at twice real-time speed. The signals will then be sampled and multiplexed at forty samples per second per channel; with the tape being read at twice the speed at which it was recorded, this sampling rate will correspond to twenty samples per second in station time. The samples will be multiplexed and digitized immediately and passed on to the input of the digital computer. In order to provide for a continuous operation and a possible minimum phase velocity of 5 km/sec, approximately 7 seconds worth of data from each trace must be stored in core memory, the "oldest" data being dropped as new data are added. In the central processor the search program is applied to the data: the proper samples are added into two sets of sums according to the various search conditions being examined, the proper members of the two sets are cross-correlated, the correlator output is integrated with a time constant of two or three seconds, and a test is applied to determine whether a coherent event has been detected. If so, output will be started automatically and various diagnostic traces will be drawn by a multi-pen recorder. All computing can take place in the intervals between input, testing, and output, and the provision of overlap facilities on the computer will ease the time problem considerably. Details of programming are left for a future paper.

The program outlined above began running on the CDC 3100 in December, 1965. Initially, the phase velocities being used are in the range 8 to 25 km/sec, corresponding to P-wave arrivals from epicentral distances less than 100°. It is hoped that initial search and first-order processing as described above will provide statistical evidence as to the lower limit of magnitude of explosions or earthquakes that can be detected and identified by this method. It is anticipated that ultimately an array similar to the one at Yellowknife will be able to detect and provide coherent information on all events down to approximately m3.5. At and above this level of magnitude it is estimated that there are more than 18,000 seismic events a year throughout the world (Joint Committee, 1960). Such a mass of data cannot be handled by hand or other analogue methods; much of it, indeed, may have to be rejected or ignored after preliminary processing. In any event the only logical way to approach the problem at this time appears to be by the high-speed digital processing method described above or some sophisticated variation thereof.

In order that secondary processing can take place, each event, as detected by the primary program, will be written onto a library digital tape. The library tapes can be read back into the computer at any time at high speed. This will allow later more intensive searching of selected events for later phases (including high apparent velocity core-reflected phases) and examination of complex crustal travel paths from nearby events. In the latter case very high resolution will be required and the accuracy of results may be limited by the array configuration.

D. PROBLEMS TO BE INVESTIGATED

The determination of the direction of first motion of the P phase on a world-wide basis was originally thought to be the best method for identification of the source (explosion or earthquake). While the theory has not been disproved, the method has been found to be impractical due to the large number of stations that would be required. No completely reliable method of identification has yet been proven, but the examination of teleseisms at third-zone distances as described below appears to show good promise. The theory of this method is more completely covered by Carpenter (1965a) and by Birtill & Whiteway (1965).

It is well known that the received P-wave energy from a seismic source varies non-linearly with distance between source and receiver. Near the source the signals are very strong but decrease rapidly in amplitude as the distance is increased from 2° to 10°. In this range also a great many phases arrive very close to one another in time, and interpretation of the record is difficult. This is because the entire travel path of the waves has been through the disturbed rocks of the crust in this "first zone".

In the "second zone", $10° \leqslant \Delta \leqslant 25°$, the signals received are very weak and variable and their beginnings are indeterminate. This is considered to be a shadow zone but the exact reason for its existence is still under investigation. The first and second zones are thus unable to supply good clear interpretable P-wave signals.

The "third zone", from 30° to 90°, has been called by Dr. Thirlaway (1965a) the "source window". Beyond $\Delta \doteqdot 90°$ diffraction through the core will introduce distortion. In the third zone the P waves have travelled up through the disturbed crust at a high angle, after having travelled most of the distance from the source in the relatively undisturbed mantle. The various phases are well separated in time and some identifications can be made by velocity filtering. As a result of these factors the various P waves arriving at a station from an event at third-zone distance are relatively simple and will be more diagnostic of the source than those arriving from other distances. In the examination of possible methods of differentiation between explosions and earthquakes we will therefore confine our attention, initially at least, to events coming from third-zone distances. In the case of Yellowknife this includes, for instance, all of the USSR, a large part of northern China, North Africa, and the southern United States.

Theoretically, an explosion in a homogeneous medium is expected to generate a simple impulse which propagates uniformly in all directions as a P phase and gives rise to all the other phases which derive from P by reflection and mode conversion. Since all the energy released by an explosion is directed outwardly from the source there should be no phases present involving S until mode conversions begin to take place. Local structure can, of course, modify this simple picture to some extent.

The signals from an earthquake, on the other hand, are generally complex. Rather than being a single shock, an earthquake may consist of a series of shocks so close together in time that all signals after the initial P tend to interfere with one another. Also in many cases earthquake energy cannot be assumed to be emanating from a point source; the source may be spread out for many miles along a fault and the energy may be generated by what has been called a "moving source", giving rise to more interference in the coda. Furthermore, an earthquake in general will have an asymmetrical radiation pattern; that is, its source mechanism will determine zones in which P or S may not be propagated at all and other zones in which one or the other of P and S may be much the larger of the two.

For the reasons given above several simple hypotheses may be considered, each of which is capable of empirical confirmation by array seismology:

(a) At teleseismic distances (i.e., in the third zone) the coda of an explosion event should contain very little coherent energy, whereas the coda of an earthquake event may contain a large amount of coherent energy. The part of the coda referred to here is that part extending after the initial P phase by 15 or 20 seconds.

(b) The amount and distribution of coherent energy contained in the initial P phase and the next 15 or so seconds of the coda should be nearly constant in all azimuths from an explosion source but should vary considerably with azimuth for most earthquakes.

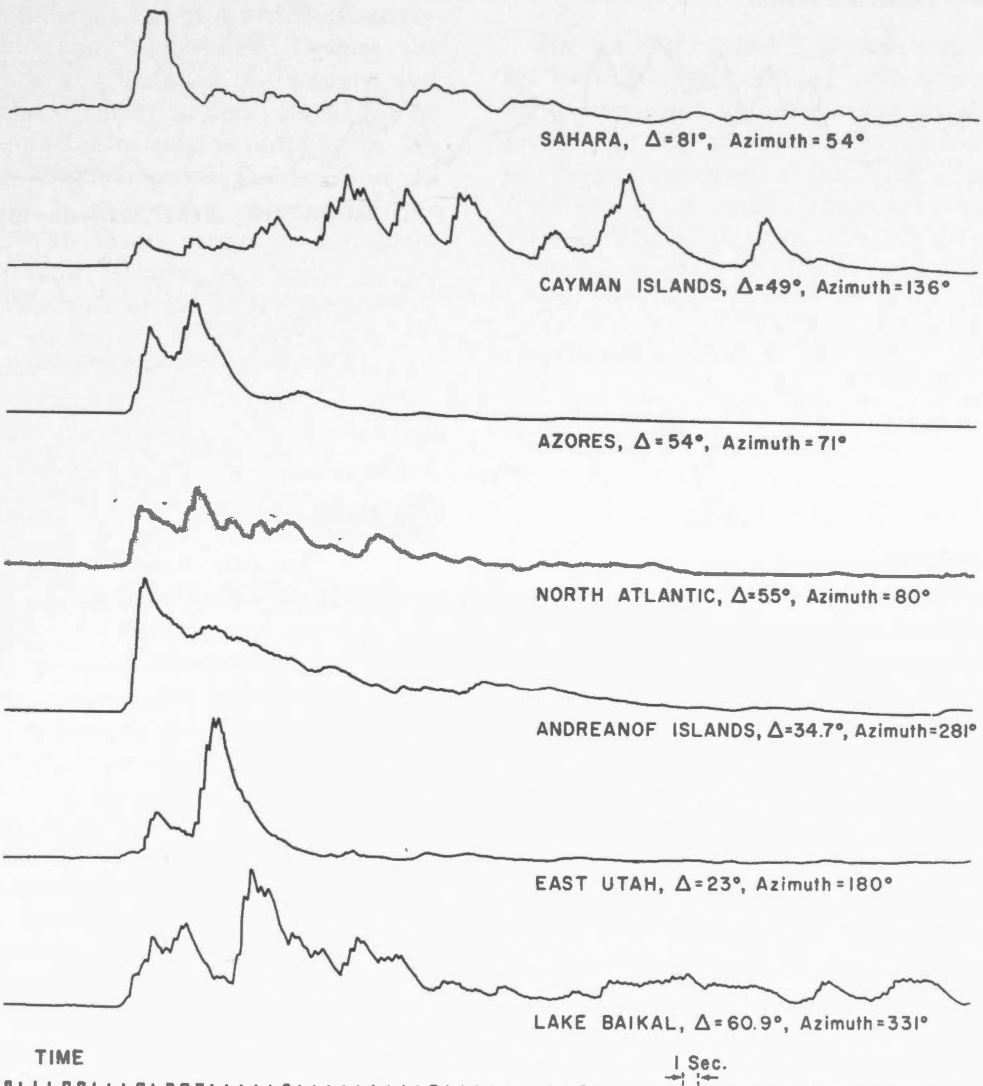

Figure 5.
Yellowknife correlator outputs for one explosion and six earthquakes.

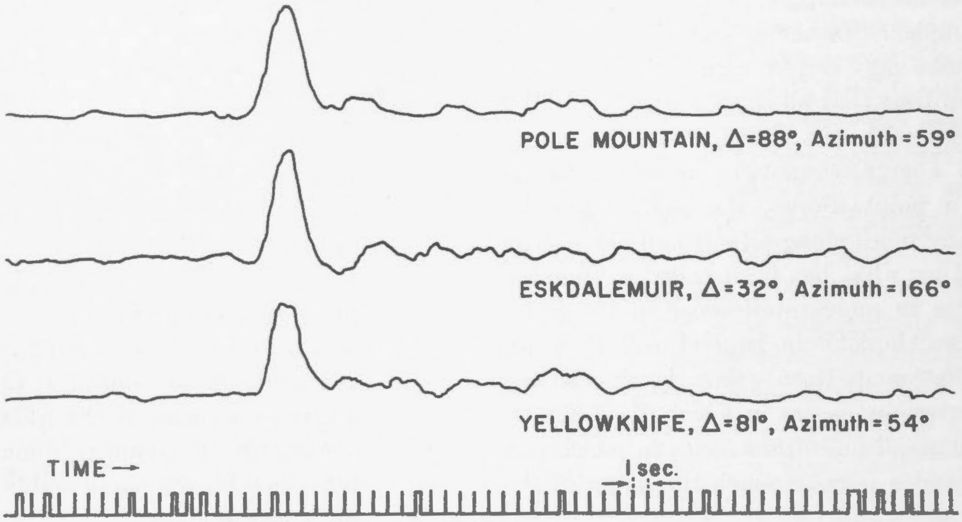

Figure 6.
Correlator outputs from three arrays for an explosion.

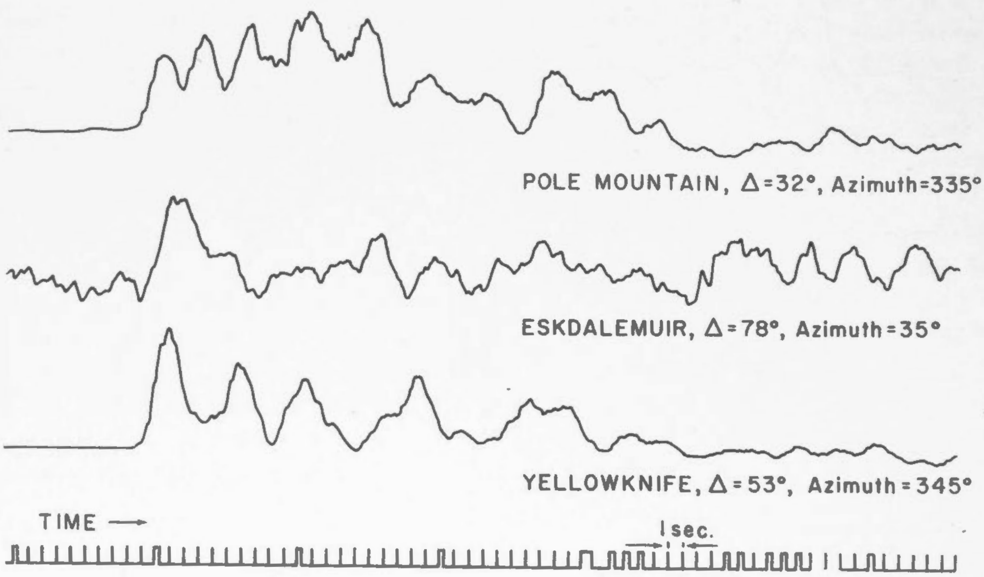

Figure 7.
Correlator outputs from three arrays for an earthquake, off coast of El Salvador,
H = 14:36:11, 11 January, 1963.

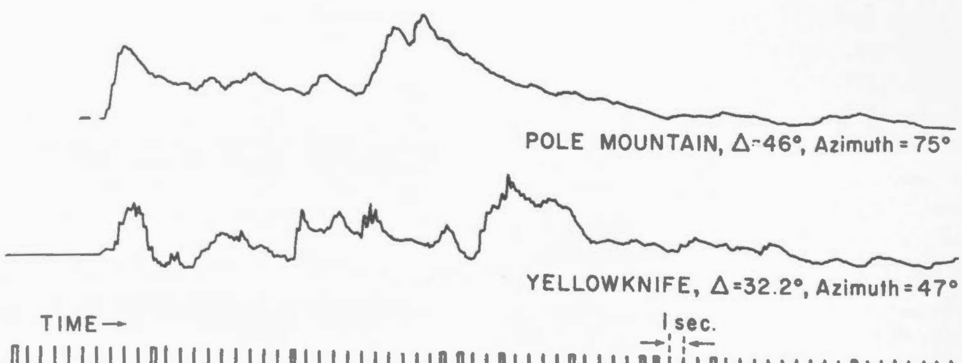

Figure 8.
Correlator outputs from two arrays for an earthquake, Andreanoff Islands, H = 08:56, 20 January, 1963.

Some tentative proof has been accumulated in support of these hypotheses (Carpenter, 1965a, b; Birtill & Whiteway, 1965; Thirlaway, 1963; Thirlaway, 1965a, b). Figure 5 shows the correlator outputs for energy from seven events recorded by the Yellowknife array and processed as described above (analogue method). The first is due to a nuclear explosion, the other six to earthquakes, and the epicentral distances and azimuths from Yellowknife are noted on each trace. It is apparent that the earthquake signals possess a large, but variable, amount of correlatable energy immediately following the initial P phase, and it must be added that these correlator outputs are typical of the vast majority of the earthquakes which have so far been examined. In contrast, the correlator output for the explosion is extremely simple, the correlatable energy lasting only a few seconds.

Figure 6 shows the correlator outputs for energy received from a single nuclear explosion in North Africa as recorded at three different UKAEA arrays, Eskdalemuir, Pole Mountain and Yellowknife. Despite the differences in azimuth and distance the amount and distribution of correlated energy is very similar for all arrays. Figure 7 shows the correlator outputs for the three arrays for an earthquake off the coast of El Salvador, and Figure 8 shows the outputs for the Pole Mountain and Yellowknife arrays for an earthquake in the Andreanoff Islands. In Figures 7 and 8 it is evident that the distribution of the correlatable energy in the coda varies widely with azimuth and distance; a reasonable inference is that this phenomenon is due to an asymmetric source mechanism. All the correlator outputs shown in Figures 5 to 8 were obtained using the proper search condition (i.e., correct azimuth and velocity) for the P phase at the known epicentral distance, filter settings of 1-2 cps pass band, and a 2-second square integration window.

The above examples are only a few of those that have been accumulated by the UKAEA over the last few years in their investigation of array seismology. Not all events give clearly identifiable signatures such as those illustrated. In general, if an explosion signal can be lifted cleanly out of the noise background it will give a simple correlator output. However, a small percentage of earthquakes of unknown depth are said to give similar records, and these are the crux of the current research problem. Work is continuing at the UKAEA establishment in England and will soon commence at the Dominion Observatory in Ottawa. As well, it is expected that the LASA (Large Aperture Seismic Array) now being built under VELA auspices in Montana will add much new information to the whole field of array seismology.

Besides the investigation of test-ban monitoring methods there are a number of fundamental seismological problems that are susceptible to attack by the use of large arrays. Seismologists have always been frustrated by the apparent complexity of the earthquake coda. By the velocity filtering and correlation techniques as applied to large arrays now becoming available it is possible to pick many, perhaps all, important phases with considerable accuracy. It is reasonable to suppose that all these phases will be picked and reported routinely by the array stations in the near future. The results of the availability of this new knowledge will be several: travel-time curves will be capable of refinement, focal-depth estimates will be improved, travel-paths will be capable of more precise delineation and this in turn will lead to more precise mapping of the internal structure and constitution of the earth. It is anticipated that the British arrays and the new American LASA will provide much material for seismological research for many years to come.

CONCLUSION

The need for control of nuclear arms and in particular for control of underground nuclear test explosions has led to important advances in the art of seismology. One potentially very powerful tool that has been developed by British scientists is the large seismological array. Evidence now available indicates that the processing of teleseismic events by large array techniques may provide a means, acceptable to all parties, of monitoring a nuclear test-ban agreement. As well, it is anticipated that large arrays will add greatly to routine seismological knowledge (Willmore, 1963). The Yellowknife seismological array has been and will continue to be a major contributor to this program.

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August, 1965.

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