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The NORSAR Array and Preliminary Results of Data Analysis

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Summary

A large aperture seismic array, NORSAR, has been constructed in Norway. The project, which started in the summer of 1967, is a joint undertaking by the governments of Norway and the United States of America. NORSAR consists of 22 subarrays, each equipped with one three-component long-period and six short-period instruments. The array diameter is around 110 km, while that of a subarray is approximately 8 km. In the data centre, which is located just outside Oslo, are installed 2 IBM 360/40 computers with peripheral equipment, a special-purpose computer, and an experimental operations console. Routine tasks performed at the data centre comprise array monitoring and calibration, data acquisition, on-line event detection and off-line event analysis. In this paper we give a technical description of NORSAR, emphasizing the software aspects of the array operation, and present some analysis results of *P* waves recorded at NORSAR. For example, we have found that signal power and spectral characteristics vary across the array and seem to reflect local differences in the geological structures at the subarray sites. The recorded signals are found to be broadband and to contain significant energy at higher frequencies. Observed signal coherencies vary considerably across the array and are usually independent of station separation. Within the subarrays signal coherence is high and the waveforms exhibit little scattering.

Introduction

Based on a request from Advanced Research Projects Agency (ARPA)* the United States government proposed to Norway in May 1967, the construction of a large aperture seismic array on Norwegian soil. The purpose of such an array was to provide data for research on seismological detection and classification problems, and to provide event monitoring functions in the possible advent of a comprehensive test ban treaty. By the end of 1967, three small experimental arrays were in operation. The analysis of data from the preliminary systems gave promising results, and in May 1968 the Norwegian parliament approved construction of a large array north-east of Oslo. The cost of NORSAR and its operation to July 1972 is mainly covered by ARPA. Field work (involving expenses of $6 million) and instrument installation were performed by the Norwegian Defence Research Establishment. For NORSAR

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* Table 1 gives a list of abbreviations used in this paper.

Phase III, characterized by recording and data centre operation and starting 1970 July 1, the local responsibilities rest with a scientific non-profit organization, the Royal Norwegian Council for Scientific and Industrial Research (NTNF). The Federal Systems Division of IBM developed the software for array monitoring, data acquisition, and analysis on a routine basis. The Electronic Systems Division, U.S. Air Force Systems Command, acts as a consultant and technical adviser for NORSAR.

The full array became operational in the spring of 1971, although interim short-period data recording and analysis have been performed for long intervals both in 1969 and 1970. The purpose of this paper is to inform our colleagues about the hardware and software capabilities of the array, as well as the research activities which make use of the NORSAR data. It is not our intention in this paper to discuss the details of the analysis results.

NORSAR configuration and instrumentation

NORSAR is located in south-eastern Norway and comprises 22 subarrays (Fig. 1) each containing one long-period (three-component) and six short-period (vertical) seismometers. The latter are in vaults or in shallow boreholes with depths ranging from 3 to 15 m. The types of long-period instruments used at NORSAR are Geotech model 8700C (horizontal) and model 7505B (vertical), which are moving coil, velocity type seismometers. The interconnected amplifiers are Ithaco, model 6083–82. The short-period sensors used are Hall–Sears HS–10–1/ARPA vertical seismometers, these are spring-mass, velocity type instruments interconnected with a Texas Instruments RA–5 amplifier. Instrument response curves are given in Fig. 2. The NORSAR configuration indicates that the response of the array is fairly symmetric. The power is down about 20 dB at a wavenumber difference of 0·01 c km^{-1}, and the worst side-lobes are not more than about 5 dB above this level.

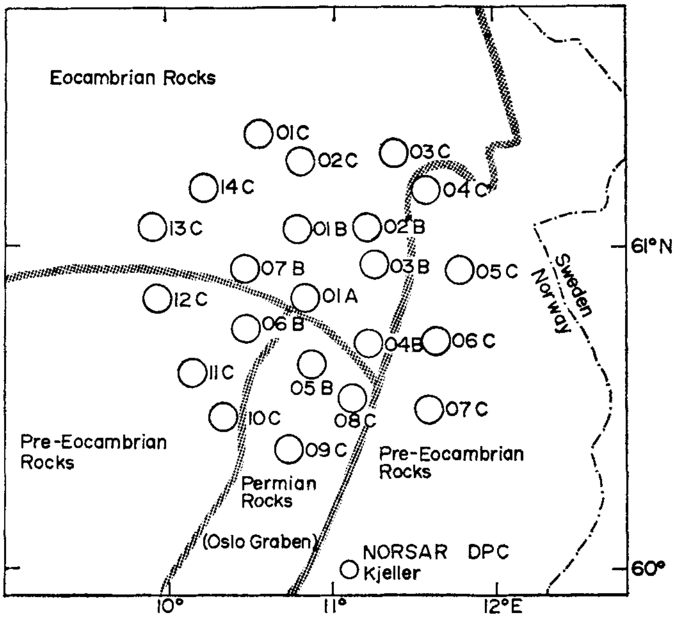

FIG. 1. NORSAR Array configuration. The geological structures in the siting area are briefly outlined.

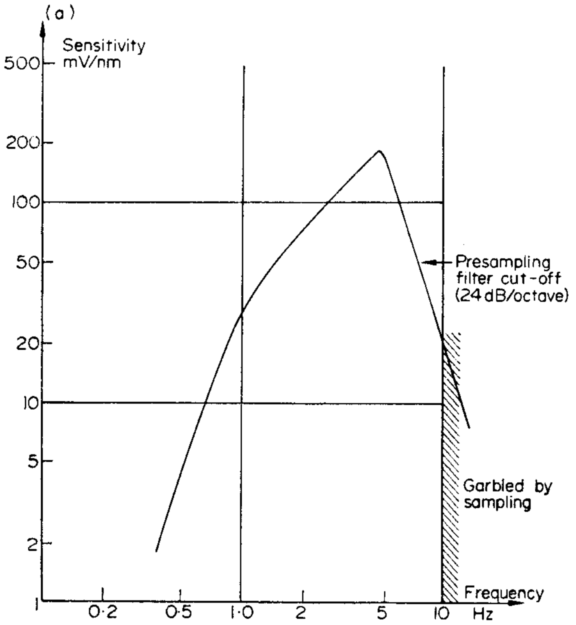

FIG. 2.(a) Short-period system response.

A brief outline of the geological structures in NORSAR siting area is given in Fig. 1. The Pre-Eocambrian rocks consist mainly of gneisses and granite. A sparagmite layer (probably 1–3 km thick) of Eocambrian age is overlaying the Pre-Eocambrian rock complexes, but in some places even covers Cambro–Silurian sedimentary rocks. The Permian Oslo graben is characterized by plutonic rocks (mainly syenites and granites) and Cambro–Silurian sedimentary rocks. Preliminary analysis indicates that the geological structures as outlined above are reflected in the *P* signal shape as a function of subarray site. For more details on the geology in the NORSAR area and in Norway itself, we refer to Holtedahl (1960). The crustal structures in

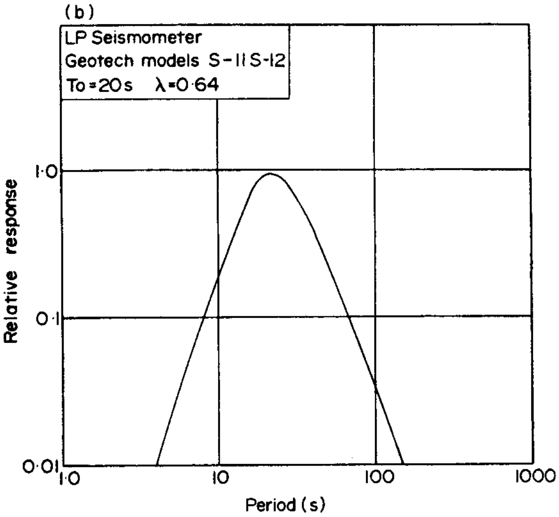

FIG. 2.(b) Long-period seismometer response.

Fennoscandian have been extensively studied by refraction shooting in recent years (see for example Sellevoll & Pomeroy 1968). In the vicinity of NORSAR, recent results suggest that the Moho has a somewhat complicated geometry (Kanestrøm, personal communication).

Data transmission and instrument calibration

From the seismometers the recorded earth motions are transmitted through amplifiers at the top of the boreholes or pits and via trenched cables to the Central Terminal Vault (CTV) at the subarray centre. The Long Period Seismometer Vault (LTV) is located nearby. The CTV is housing the Short and Long Period Electronic Module (SLEM) which multiplexes and digitizes the nine seismometer outputs into a single bit stream. The sampling rate is 20 and 1 Hz for short-period and long-period seismometers respectively. To avoid aliasing, analogue filters with high-frequency cut off at 4·8 Hz are part of the SLEM. The data are transmitted each 0·05 s by means of ordinary telephone lines (2400 baud) to the NORSAR Data Processing Center (NDPC) at Kjeller for further analysis.

There is, of course, a two-way data flow between the respective subarrays and NDPC, as time synchronization signals are sent to the SLEM each 0·05 s. In addition, special commands may be sent to the SLEM from the Experimental Operations Console (EOC) for activating signal generators (sine pulses or pseudo-random waves) to test and calibrate seismometers, SLEM, and data transmission lines.

Drift of the long-period seismometer mass position can be corrected remotely from NDPC by start and stop commands to small electromotors in these instruments. A display on the EOC enables the operator to check the status of any seismometer or subarray, and the CTV and LTV information about open doors and possible water accumulation in the vaults can also be obtained. Statistics on the performance of the transmission system are printed out regularly as an aid to localize and correct hardware errors which may always occur within a system of NORSAR's complexity.

The NORSAR transmission system, with a capacity of about 50,000 baud of continuous data flow, makes NORSAR one of the largest on-line data transmission systems in Europe. In addition, one trans-Atlantic link of 2400 baud is used for on-line long-period data transmission and communication between NORSAR and the Seismic Array Analysis Center (SAAC) in Alexandria, Virginia, which also connects with the Large Aperture Seismic Array (LASA) in Montana and the Alaskan Long Period Array (ALPA).

Data processing

The data received at NDPC are processed and stored on magnetic tape for a predefined retention period. The routine data analysis is performed in two steps: detection processing (on-line) and event processing (off-line). The array monitoring and calibration functions are executed independently of the above analysis. Before we give an outline of the software system, it is appropriate to dwell briefly on the computers and peripheral equipment installed at NDPC, which are shown in Fig. 3. It is a dual computer configuration, i.e. the IBM 360/40 and related equipment such as tape and disc drives used for detection are identical to those for event processing. This means that continuous data recording and on-line analysis capabilities are retained also during the regular machine service periods. However, there is no duplicate of the Special Process System (SPS). Neither is there a duplicate of the EOC, but unlike the SPS this unit is not vital for the data recording and analysis.

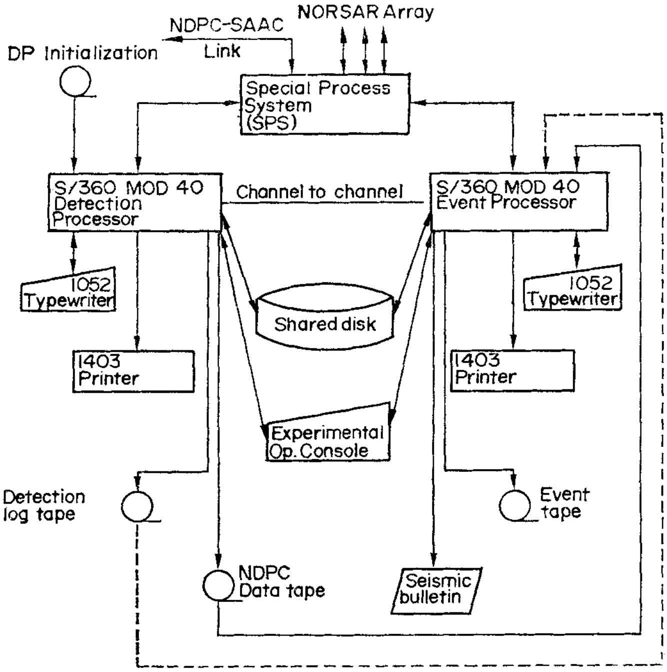

FIG. 3. Hardware configuration of the NORSAR Data Processing Center (NDPC).

Detection processing

The Detection Processor (DP), outlined in Fig. 4, performs all functions associated with data acquisition and array monitoring. The DP also processes the incoming data in real time and decides whether or not a detection of a seismic event should be declared. The programs are divided in seven tasks, where data acquisition and tape writing have the highest priorities. This ensures that the recording takes priority over all other tasks in case of system overload. Several error checks are carried out in the SPS, which transfers data each 0·5 s to the DP. Detected errors are indicated on the output tape, thus ensuring the integrity of the recorded data. The SPS also performs some preprocessing of the seismometer signals in order to relieve the DP of some processing load. This processing includes recursive filtering with two filters, A and B, and the forming of up to 20 subarray beams per filter for each of the 22 subarrays. These beams are slightly dispersed in order to decrease the maximum signal power loss in the subsequent array beamforming.

The Detection Processing task uses the subarray beams from the A filter as input to the array beamforming process. Up to 400 array beams may be formed by the DP, which includes options for additional filtering on the array beam level. These beams, which constitute the so-called Selected Surveillance, are steered towards the most interesting seismic regions. Due to the large aperture of NORSAR, this number of beams cannot cover adequately the whole teleseismic region of the array. A General Surveillance, using subarray beams from both filters, is therefore performed in parallel with the Selected Surveillance. It covers the whole teleseismic region, but with a lower detection capability.

The detection algorithm, performed individually on each subarray or array beam, is the following: The beam is rectified and integrated over a sliding time window (length around 2 s), resulting in a short-term average (STA). A long-term average (LTA), is calculated by a recursive algorithm, provides a noise estimate which in principle is based on the history of the beam from the time the system was activated.

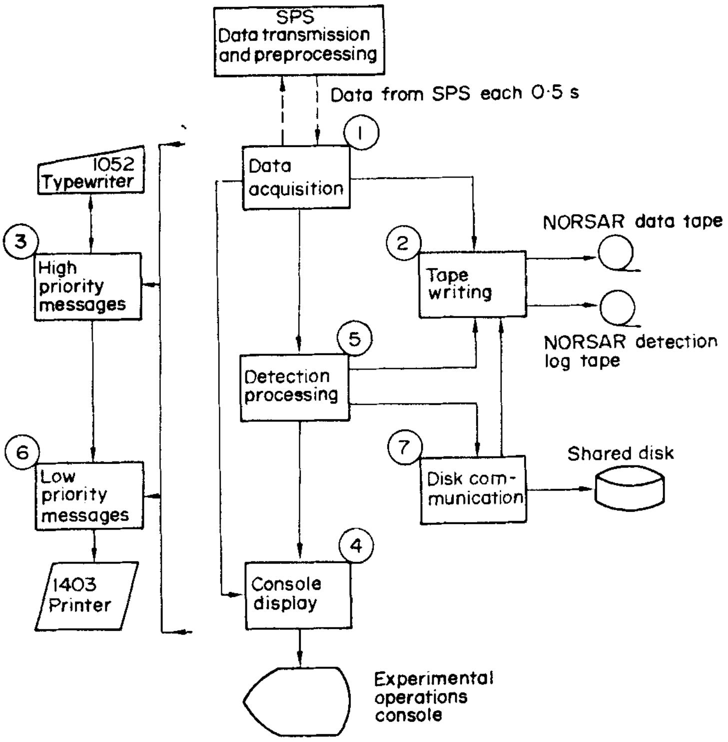

Fig. 4. NORSAR Detection Processor. Task numbers are encircled.

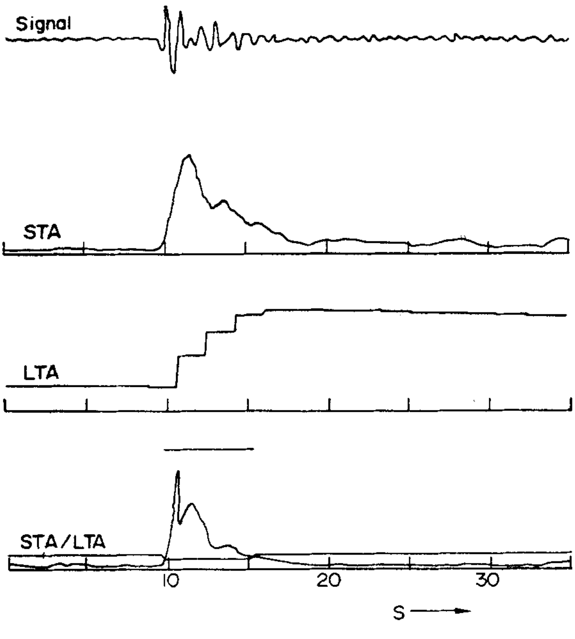

Fig. 5. Beam, STA, LTA and STA/LTA for earthquake from Tsinghai, China; arrival time Jan 27 1970, 10.59.40.1 filtered 1·0–3·0 Hz. STA integration time is 1·8s, and LTA computation rate is 5/9 Hz. The short line above the STA/LTA curve indicates detection state, and the line crossing the curve is the threshold.

The amplitude ratio STA/LTA is calculated at a specified rate for each beam. Whenever this ratio exceeds a certain threshold for a predefined time interval, a detection is declared on the corresponding beam. Fig. 5 shows an example of these calculations.

A seismic event may cause detections to be declared on several beams. This requires activation of a reduction process which in essence consists of finding the beam with the largest STA within the group of detections. In addition, the process checks if the locations of the largest beams are close enough together to ensure that it is not a false alarm. Whenever a detection has been declared, the start and end times, approximate location, and magnitude of the detected event are written on the shared disk, which later will be read by the Event Processor.

The DP may also communicate with the EOC during on-line processing. Up to eight signal traces can be displayed in real time on the Waveform Display, which can hold 45 s of data, including seismometer values and array beams. The Beam Display of the EOC can display in inverse velocity space all rectified and integrated array beams (or subarray beams) as illuminated squares whose intensities are proportional to the STA values.

Event processing

The Event Processor (EP) outlined in Fig. 6 satisfies two objectives: first, the preparation of a daily seismic bulletin; and second, support of seismic research through the formation of a seismic data base. The EP receives the detections and preliminary epicentre determinations from the DP, and it contains algorithms required to assign seismic phase identifications to the detections reported by DP and to group together the detections which belong to the same event. The EP also selects events for further processing, in which different short period seismic parameters are extracted. Processing of long-period waves will commence in summer 1971. This software package, developed by Texas Instruments, includes spectral, coherence, and wavenumber analysis, and options for multichannel (Wiener), match, and bandpass filtering.

As Fig. 6 indicates, the output from the DP first enters the Event Process Controller (EPCON), which organizes the detections into event families in a Detection File.

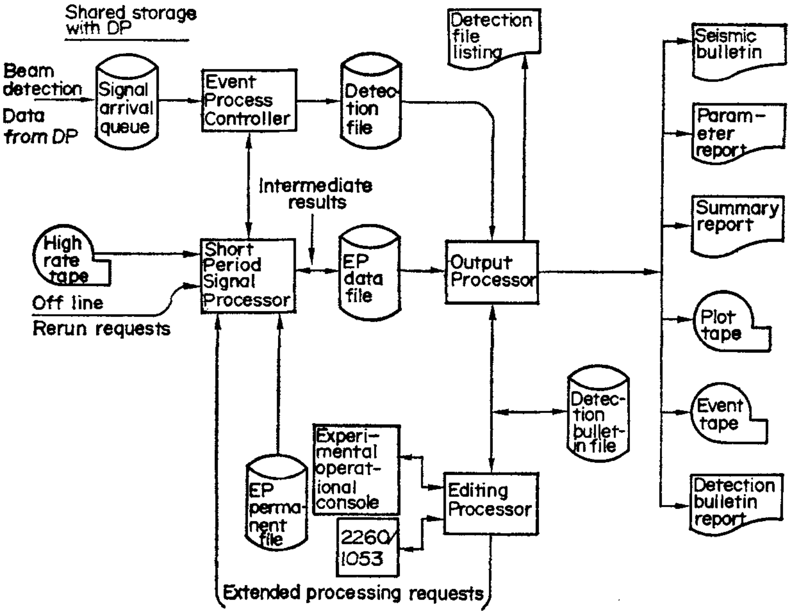

Fig. 6. NORSAR Event Processor

The EPCON then communicates with the Short Period Signal Processor (SPSP), which calls for raw data from High Rate Tape and, for example, regional corrections, from a permanent EP file in order to provide the EPCON with more detailed information about each event. The SPSP creates an EP Data File to produce a daily seismic bulletin, event tapes, plot tapes, a summary report, a parameter report, and a Detection/Bulletin report. The Output Processor also creates a Detection/Bulletin File, which the Editing Processor uses, together with the EOC and a 2260 Display Unit to allow the operator to edit the results and, if desired, to request extended processing.

The Event Processor Controller constitutes the main logic and control portion of the process. It starts with the merging of the DP detection groups from both the general and the selected surveillance beams, and the assignment of a seismic phase identification to each detection group. In order to keep the EP work load at a reasonable level, EPCON may change the EP threshold and thus determines whether or not a detection group will be processed by the SPSP. This criterion depends on signal phase, amplitude, signal-to-noise ratio, and the amount of computer time available in the processor. The EPCON also reviews selected results from the SPSP and modifies the initial phase identification if required, and finally it updates the Detection File for each detection group.

The Short Period Signal Processor (SPSP) is called upon by EPCON, and contains algorithms for extraction of more detailed information about the short-period signal phases selected for further processing. The SPSP gives as output the wave parameters needed in the bulletin, waveform data, intermediate process results, and selected review parameters. Included here is location in inverse velocity space, arrival time, depth phases with arrival times, and results of converting from inverse velocity space to geographical co-ordinates.

The SPSP consists of three components: inverse velocity space estimation, waveform parameter extraction, and event characterization. The location of the signal arrival in inverse velocity space is calculated by using the detection data as a starting point. The time alignment of the subarray beams which yields the array beam with the maximum signal-to-noise ratio is determined by using a cross-correlation iterative technique for events with sufficiently large signal-to-noise ratio. The different subarrays are weighted according to the calculated correlation coefficients and signal-to-noise ratio of the subarray beams. A linear sequential estimation algorithm is introduced for fitting a least-squares plane wave to the derived delays. The resulting array beam and location in inverse velocity space are then passed on for further analysis.

Some basic signal parameters are extracted from the array beam waveform. The magnitude is determined by an algorithm based on the assumption that the signal power is proportional to the kinetic energy of the *P* waves, as the short-period instruments are essentially velocity measurements devices (the kinetic energy is included in the magnitude definition through the inclusion of the A/T term). Arrival time is computed either by a threshold pick (emergent events) or by a model fit (impulsive events). The dominant period is estimated by power spectral analysis; the signal amplitude is then calculated on the basis of dominant period and magnitude.

Data analysis

An interim NORSAR data recording system comprising 18 short-period seismometers from different subarrays became operational in January 1970. Data from about half a year have accumulated in this way, and preliminary analysis results are discussed in this section.

The most important task has been to calculate precise time anomaly corrections (Bungum & Husebye 1971); about 260 good events have been used. The measurements are computerized (IBM 1967) and used to establish a library of regional time delay corrections, which are defined as the deviations from a plane wavefront. High accuracy in time delay data is essential, as the estimated loss in array gain due to timing errors is (Steinberg 1965):

$$\text{Loss} = 170(\sigma/\tau)^2$$

where σ is the standard deviation of the time delays, and τ the dominant signal period, and loss is in decibels. This effect has been verified empirically using 18 strong events for which time delays were measured accurately. The average signal power loss in the beamforming process was $2{\cdot}0 \pm 0{\cdot}1$ dB (due to signal incoherency), while the corresponding value using delays calculated on the basis of a plane wave assumption was $5{\cdot}7 \pm 0{\cdot}5$ dB. This means that the average loss due to lack of steering delay corrections was around 3·7 dB. The importance of this effect is demonstrated in Fig. 7, where individual sensor traces and array beams with and without time delay corrections are displayed for two earthquakes. Noise suppression came close to the theoretical value for 18 uncorrelated sensors, namely 12·6 dB. Measured time delay

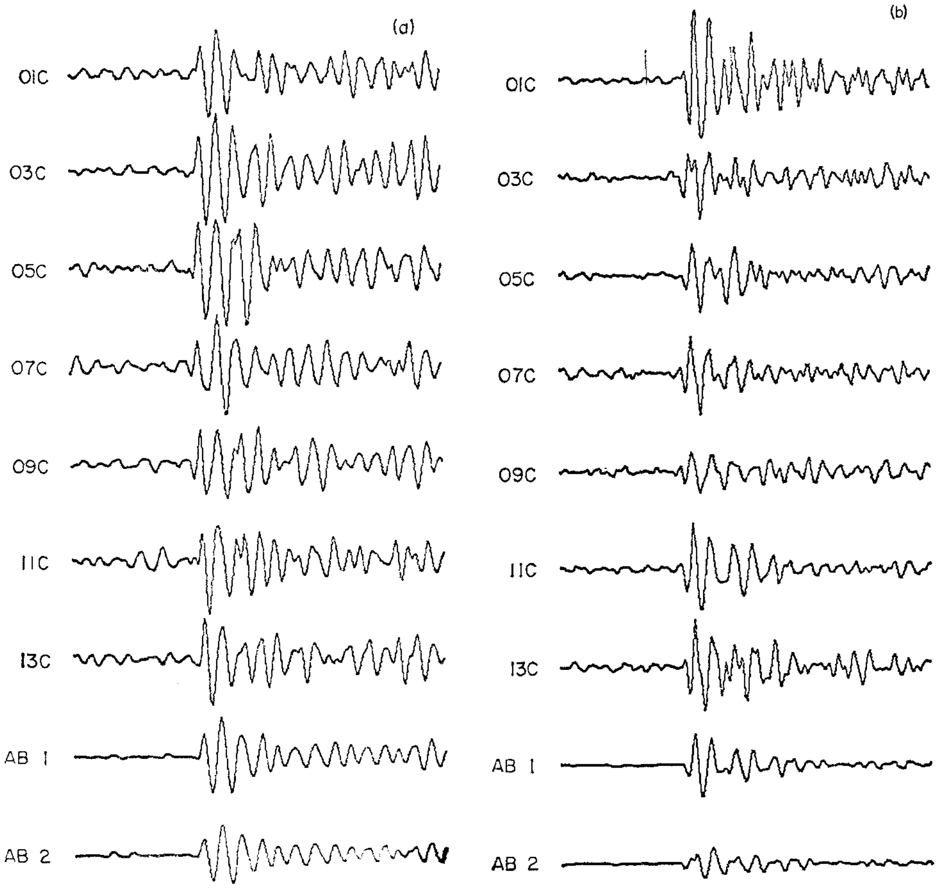

FIG. 7(a) Unfiltered P signals from seven subarray centre seismometers in the C-ring. AB1 and AB2 are beams with and without time delay corrections, respectively. The earthquake is from Unimak Islands, arrival time 1970 Jan 20, 00.49.08.9.

(b) Unfiltered P signals from seven subarray centre seismometers in the C-ring. AB1 and AB2 are beams with and without time delay corrections, respectively. The earthquake is from Tsinghai, China, arrival time 1970 Jan 27, 10.59.40.1.

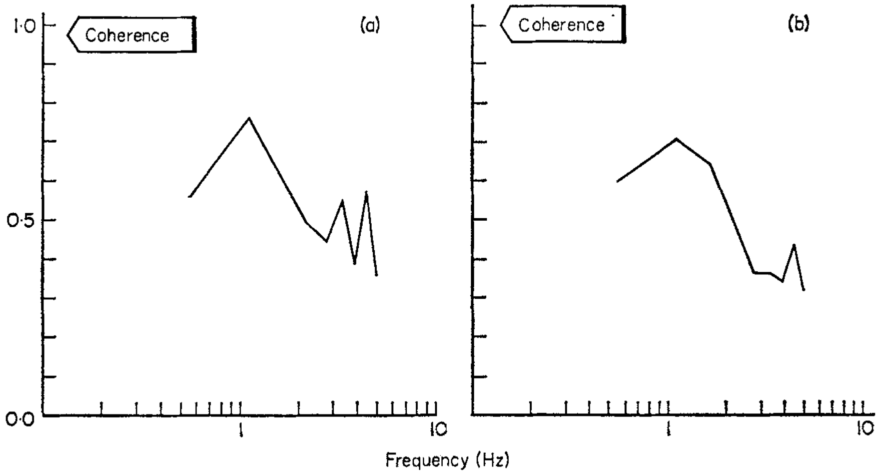

FIG. 8(a) Average coherence between 18 subarray centre seismometers, as a function of frequency. The earthquake is the same as in Fig. 7(a).

(b) Average coherence between 18 subarray centre seismometers, as a function of frequency. The earthquake is the same as in Fig. 7(b).

corrections vary in general between ±0·5 s across the array. Azimuth and $dT/d\Delta$ calculations give results which sometimes deviate significantly from those predicted from reported hypocentre parameters; such anomalies may be due to heterogeneities in the site and source regions.

Concerning signal similarity across the array, our results obtained so far indicate that this is to some extent dependent on the geology in the siting area (see Fig. 1). To measure this, signal coherencies have been computed for 22 large-magnitude events. The length of the time window used was 6·4 s and the maximum lag 15 per cent, which corresponds to about six degrees of freedom (Blackman & Tukey 1959; Amos & Koopmans 1963). For a 90 per cent confidence interval, a true coherency of 0·8 would give an observed value between 0·60 and 0·94, and a coherency of 0·4 would be measured in the range of 0·17–0·79 (Amos & Koopmans 1963). Our coherency calculations show significant variations from one event to another, but also between different sensor pair combinations. For distances greater than 10 km the coherency seems to be independent of station separation, and it is in the worst cases almost randomly distributed between 0·3 and 0·9 for frequencies in the range 1·0–3·0 Hz. Most of these adverse effects were caused by a few subarrays in the Oslo graben area (Fig. 1). However, for shorter distances, i.e. within a subarray, the geological structures is uniform enough to allow signal coherencies around 0·7–0·95 over a broad frequency band. Therefore, signal power loss on the subarray level is expected to be small, provided the time delays are sufficiently accurate. Fig. 8 shows computed coherencies for the signals displayed in Fig. 7. Signal amplitude and maximum crosscorrelation coefficients (sensor-beam combinations) vary considerably, but in general the highest values are found for sensors in the north-eastern quadrant of the array. Also in this case the 'worst' subarrays seem to be those situated in the Oslo graben.

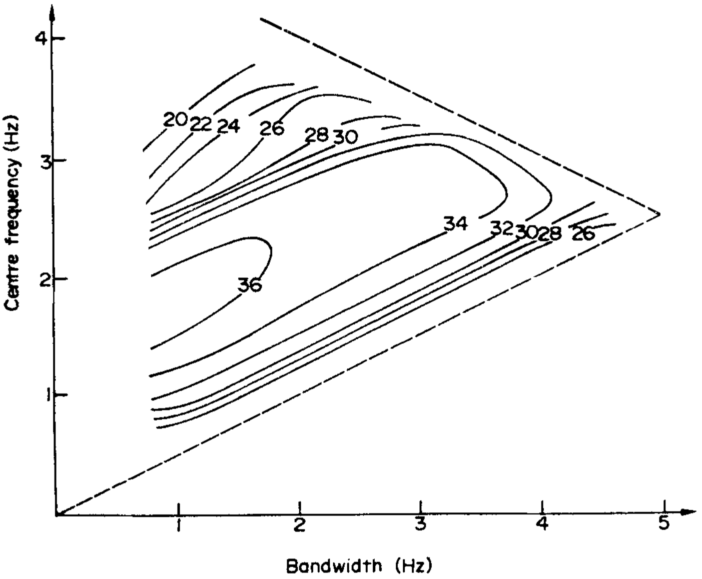

FIG. 9. Signal-to-noise ratio for an earthquake at Honshu, Japan, arrival time Jan 29 1970, 06.03.22. The measurements are performed in the time domain, using a 30-s noise interval and a 3-s signal interval. The signal-to-noise ratio parameter is computed through a large number of third order Butterworth bandpass filters, constituting the 'filter space'. The contour interval is 2 dB.

Power spectra calculated from *P* signals recorded at NORSAR are characterized by significant energy content for frequencies up to 4 Hz. Thus, in principle, NORSAR signals give more information about source parameters than the corresponding but relatively low frequency observations at LASA. However, on the beam level the difference between the two arrays is less since a significant part of the high-frequency energy is lost due to small errors in the steering delays and due to signal incoherency. A viable alternative to beamforming for obtaining spectral information at higher frequencies is spectraforming, as demonstrated by Lacoss & Kuster (1970). Observed spectral minima for the individual subarrays are to some extent independent of source regions, and henceforth should be interpreted in terms of site structures. So far, satisfactory models for explaining this phenomenon have not been found.

A major objective of analysis on interim NORSAR recorded signals was to obtain the best filter setting for the Detection Processor. Since all beams are passed through the same recursive filter, it must be chosen to give the best average performance. The information required is sought through traditional power spectral analysis and calculation of the time domain signal-to-noise ratio. In the latter case we used a large number of bandpass filters, where bandwidth and centre frequency are perturbed in steps of 0·4 Hz. Typical results are displayed in Fig. 9, where the values of signal-to-noise ratio are plotted in filter space, consisting of bandwidth and centre frequency. The figure shows that the signal-to-noise ratio decreases both toward lower frequencies (coherent noise) and toward higher frequencies (incoherent signals). The most important single parameter here is the lower cut-off of the filter which reflect the relative insignificance of the higher signal frequencies. From this study of signal-to-noise ratio, we concluded that a 1·2–3·2 Hz bandpass filter is the best compromise. On the other hand, in order to increase signal coherency, a filter with a lower cutoff of 0·9 Hz is presently used in the Detection Processor.

Table 1

Abbreviations used in this paper

ARPA	Advanced Research Projects Agency
CTV	Central Terminal Vault
DP	Detection Processor
EOC	Experimental Operations Console
EP	Event Processor
EPCON	Event Processor Controller
LTA	Long-Term Average
LTV	Long-Period Seismometer Vault
NDPC	NORSAR Data Processing Center
NORSAR	Norwegian Seismic Array
NTNF	Royal Norwegian Council for Scientific and Industrial Research
SLEM	Short- and Long-Period Electronic Module
SP	Short-Period
SPS	Special Processing System
SPSP	Short-Period Signal Processor

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NORSAR,
Royal Norwegian Council for Scientific and Industrial Research,
Kjeller,
Norway.

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