NORSAR

Seismological Verification of a
Comprehensive Nuclear Test Ban

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SEISMOLOGICAL VERIFICATION OF A COMPREHENSIVE TEST BAN TREATY

by

Frode Ringdal, Director, Norwegian Seismic Array

1. Introduction

The purpose of this presentation is to give a brief introduction to some of the problems involved in the verification of a potential Comprehensive Nuclear Test Ban Treaty (CTBT).

As is well known, a CTBT has been a major goal in disarmament talks for several decades. The fact that such a treaty still has not been achieved is due to a number of factors, both of political and technical nature. However, it is fair to say that one of the major obstacles in CTBT negotiations has been to ensure a verification capability acceptable to all parties. This will be the subject of my presentation, and I will in particular address the current status of verification by seismological means. As will be seen, international cooperation in exchange and analysis of seismic data will be essential for an effective verification system, and we expect the Norwegian seismological facilities to form a key element in this regard.

It is no coincidence that the science of seismology has had a central position throughout the negotiation of verification procedures for a CTBT. In fact, at a distance from the source, a nuclear explosion conducted undeground can only be detected by recording the strong pressure waves that are generated, and that propagate through the earth in the same way as seismic waves generated by earthquakes. After the Moscow treaty of 1963, most of the nuclear countries have conducted their weapons tests underground (see Figure 1), and testing in this environment causes by far the most difficult verification problems.

2. Review of earlier developments

The issue of a ban on nuclear testing was first raised in the 1950s, mainly as a result of wide-spread public concern over the effects of radioactive fallout from atmospheric testing. Over the years, a number of important nuclear disarmament treaties, conventions and agreements have been concluded, e.g.:

- Antarctic Treaty
- Limited Test Ban Treaty
- Outer Space Treaty
- Treaty of Tlatelolco
- Non-Proliferation Treaty
- Sea-Bed Treaty
- Threshold Test-Ban Treaty
- Peaceful Nuclear Explosion Treaty.

It is beyond the scope of this presentation to go into any detail on these treaties. I will only briefly outline some of the historical developments that are most directly relevant to the seismological CTBT verification problem of today.

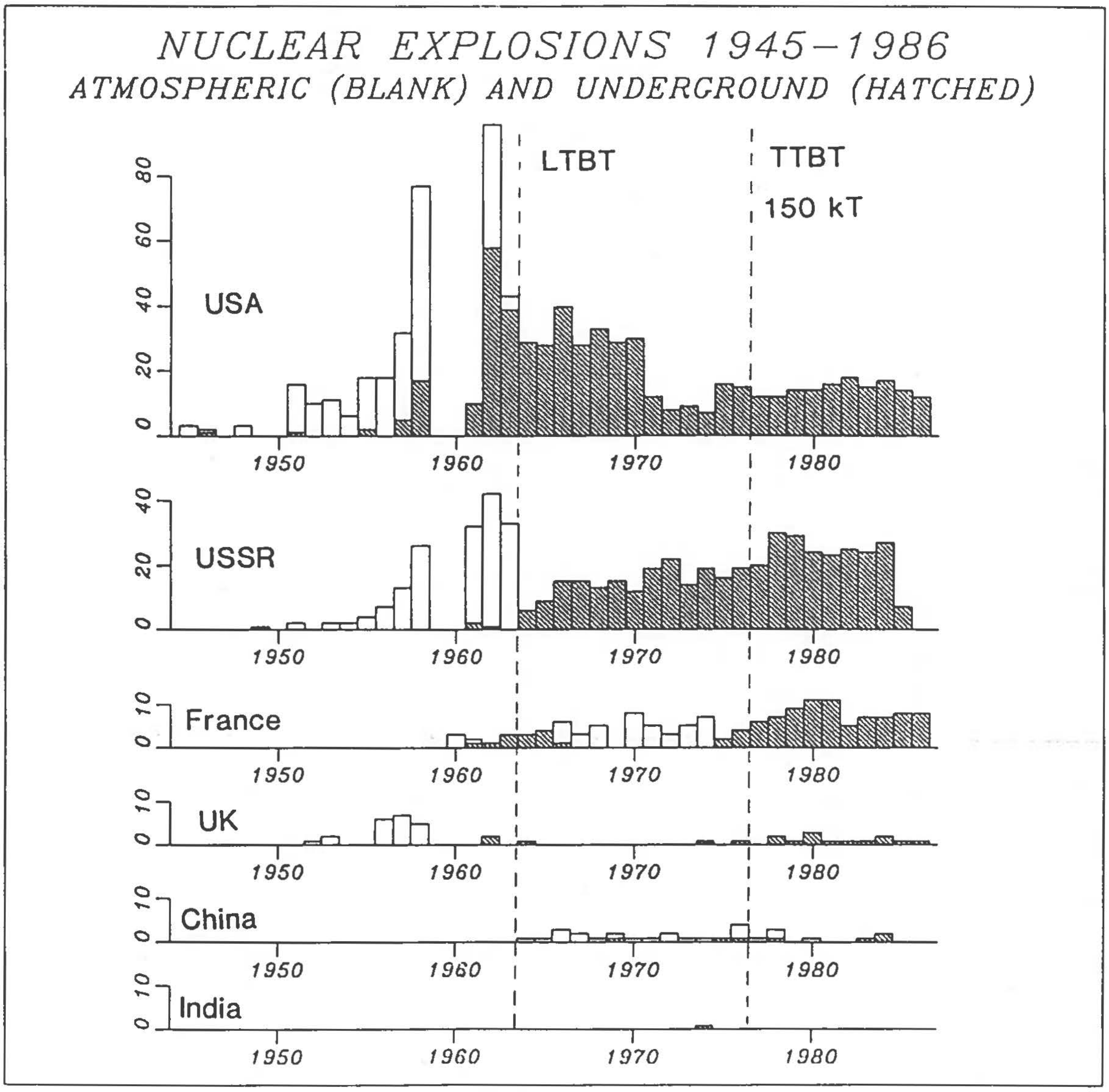


Fig. 1 Annual number of nuclear explosions conducted by six countries. Note that the Limited Test Ban Treaty (LTBT) of 1963 did not significantly reduce the number of tests, but merely caused the signatories to conduct their testing underground. The Threshold Treaty (TTBT) of 1976, although not ratified, did contribute to reduce the yields, but not the number of nuclear test explosions.

2.1 The Conference of Experts - Geneva 1958

At the invitation of the United Nations Disarmament Commission, an International Group of Experts met in Geneva in 1958 to study the technical aspects of nuclear test ban verification. Particular attention was given to the problems of detecting and identifying underground explosions, and the Group made recommendations which proved to have a far-reaching effect on subsequent developments. For example, the Group envisaged the need for a homogeneous network of globally distributed seismograph stations of high sensitivity and an efficient system for international data exchange. It further introduced the concept of arrays of closely spaced sensors to improve the detectability of seismic signals. Evasion possibilities such as hiding an explosion in the "wake" of nearby earthquakes were also foreseen.

2.2 Multilateral Test Ban Negotiations - 1962 to present

In 1962 nuclear test ban negotiations entered a new forum: the Eighteen Nation Disarmament Conference (ENDC). For the first time, non-nuclear and nonaligned states became actively engaged in technical discussions on the arms control and disarmament process with the superpowers. These negotiations have since continued in the ENDC and its successor bodies. Today, the Conference on Disarmament, or CD, comprising 40 Member States, remains the single multilateral forum for arms control and disarmament negotiations. The CD and its predecessor bodies have consistently had the CTBT issue as a priority topic on the agenda.

2.3 The Limited Test Ban Treaty (LTBT) of 1963

The LTBT signatories are prohibited from carrying out nuclear explosions in the atmosphere, in outer space and under water. Moreover, no underground tests are permitted that could result in radioactive contamination outside the country conducting the test. This treaty is multilateral and has been signed by more than 100 countries and ratified by more than 90, including the U.S. and the U.S.S.R.

2.4 The Threshold Test Ban Treaty (TTBT) of 1974

This is a bilateral treaty between the U.S. and the U.S.S.R. prohibiting the parties from carrying out any nuclear weapons test whose yield exceeds 150 KT, the verification of which is to be provided for by National Technical Means. It is important to note that this treaty has provisions for exchange of geological and geophysical data from test sites for calibration purposes such a better yield estimates, etc. Both the U.S. and the U.S.S.R. have signed the treaty, which became effective in 1976, but since the treaty has not yet been ratified by both of the parties, no data exchange has taken place.

2.5 The Peaceful Nuclear Explosion Treaty (PNET) of 1976

Nuclear explosions can also have civil applications like excavating underground storage rooms, cracking of oil shales for more efficient outflow of hydrocarbons, etc. With a view to potential test aspects, the PNET limits the yield of individual, so-called peaceful explosions to 150 KT. If a series of PNEs are to be fired, the total yield is limited to 1500 KT. The TTBT and PNET are similar in many respects; bilateral, renewable every five years, signed but not ratified by both parties, including provisions for data exchange, and so forth.

2.6 Trilateral CTBT Negotiations - 1977 to 1980

In 1977 trilateral CTBT negotiations between the USSR, UK and US commenced in Geneva. Before these talks were suspended in 1980 significant progress had been made on many critical issues (Reference: CD/130). The three negotiating parties reached agreement on a number of verification measures, including arrangements for on-site inspection for the purpose of ascertaining whether or not a seismic event was a nuclear explosion. Other such measures included international exchange of seismic data and exchange of supplemental seismic data from internal high-quality stations of agreed characteristics.

2.7 CD Seismic Verification Initiative - 1976 to present

The Conference of the Committee on Disarmament established in 1976 an Ad Hoc Group of Scientific Experts to Consider International Co-operative Measures to Detect and Identify Seismic Events. This Group, which is at present conducting its work under the auspices of the Conference on Disarmament, has provided valuable contributions to the technical problems involved in CTBT verification, and I will return to a more detailed discussion of its work later in this presentation.

3. Seismological background

Since most of you are not familiar with seismology, I will briefly describe some of the basic seismological concepts relevant to the verification issue.

A natural starting point is the global occurrence of earthquakes. As shown in Figure 2a, most of the world's earthquakes occur along narrow, well-defined zones in certain geographical areas. It is now generally

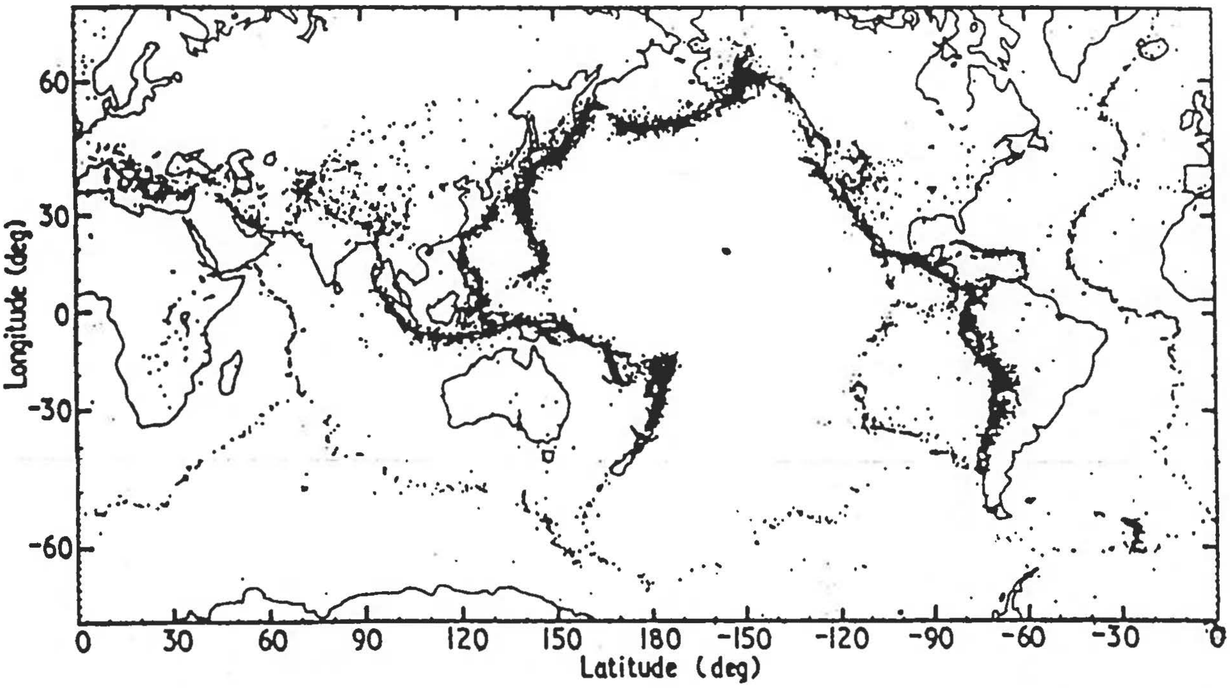


Fig. 2a Earthquake occurrence world-wide (above m_b 4.5) for a 7-year period. Note that most earthquakes occur along narrow belts, corresponding to the boundaries of the mentioned large lithospheric plates.

acknowledged that this is due to very slow relative motion (only a few centimeters per year) of large, so-called lithospheric plates, on which the continents and oceans rest. The major earthquake activity takes place along the boundary of these plates.

When an earthquake or an underground explosion, even of moderate size, occurs, it naturally causes strong shaking of the ground which can often be felt at close distances. More importantly, these vibrations propagate through the interior of the earth and can be recorded several thousand kilometers away by very sensitive instruments, so-called seismometers. Modern seismometers are capable of recording extremely small vibrations, even of the order of one millionth of a millimeter ground motion. This forms the basis for remote detection of seismic events, and is the reason for the importance of seismology in a test ban verification context.

The propagation of energy from a seismic event (earthquake or explosion) is illustrated in Figure 2b. In general, we separate between two main forms of seismic energy (or seismic waves):

- Body waves (P and S) which propagate through the deep interior of the earth

- Surface waves, which propagate along the earth's uppermost layers.

Both of these wave types are important in seismic verification, as we shall see later.

As for now, I will proceed by discussing in some detail the three basic problems in seismic verification, which briefly can be formulated as follows:

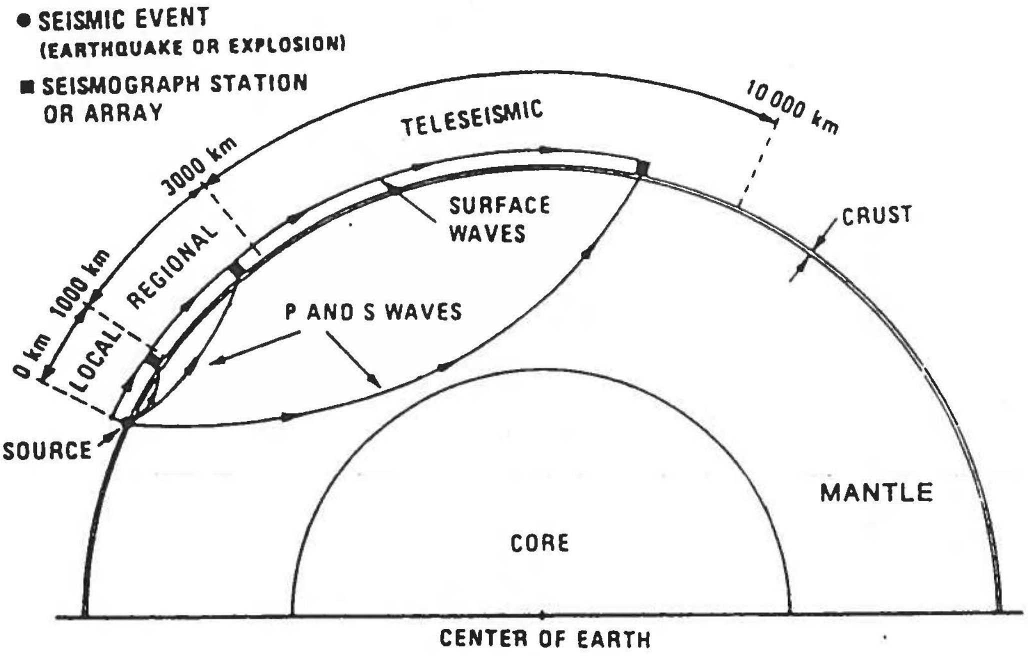


Fig. 2b Cross section of the earth showing ray paths of various types of seismic waves. The local, regional and teleseismic distance ranges, as discussed in the text, are indicated.

Detection: Did a seismic event (earthquake or explosion) occur?

Location: Where did it occur?

Identification: Was it an earthquake or an underground explosion?

4. Detection of seismic events

At modern seismological observatories, the small earth vibrations sensed by the seismometers are converted to electronic pulses and transmitted to a central computer for recording on magnetic tape or other media. To obtain a visual impression of the recordings, it is customary to plot the vibrations along a time axis, as illustrated in Figure 3.

Most of the time, the seismic recordings consist of continuous, small-scale vibrations that represent the ever-present seismic background noise. The noise is caused by environmental factors such as wind, rivers or coastal surfs, or by man-made factors such as traffic or industrial activity. Figure 3 shows how the arrival of signal energy from a seismic event can be identified by a sudden change in the size and characteristics of the recorded waveform. For a strong signal, this is easy to notice, but in the case of weak signals, it may be much more difficult to distinguish the signal from the background noise. Clearly, there will always be a lower limit as to how small earthquakes or explosions can be detected for any given seismograph station.

To determine this lower limit, or detection threshold, is of fundamental importance in assessing seismic verification capabilities. The threshold clearly depends on a number of factors, such as the strength of the background noise, the distance from the source and the propagation efficiency of waves from the seismic event.

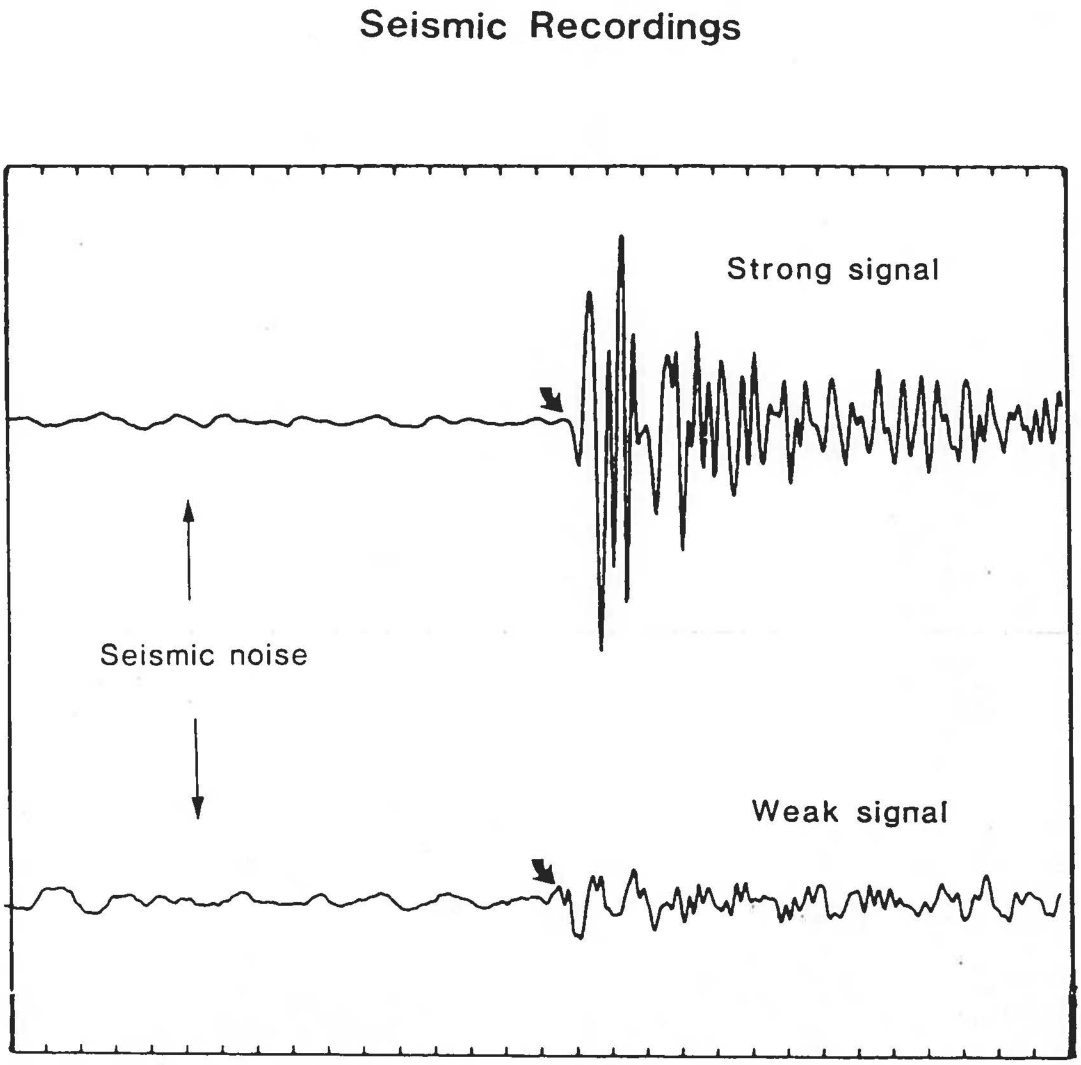


Fig. 3 The arrival of seismic wave energy at a station is observed as a sudden change in the character of the recorded vibrations (arrows on figure). For small events, the onset of the weak signals produced may often be difficult to separate from the background noise.

In order to obtain best possible detection, several factors are important. First, the seismic stations must be located in areas as far removed from seismic noise sources as possible. The seismometers should ideally be emplaced in geological areas with good propagation characteristics for seismic waves, and preferably installed directly on hard rock. Finally, it is necessary to have a network of stations distributed globally, so that for each seismic event, at least some stations will be within a favorable distance range for detection.

Very local effects can cause an important difference in signal detection possiblities. As an example, recorded seismic waveforms at the NORSAR array for a presumed explosion at Semipalatinsk are shown in Figure 4. The strong signal energy recorded at some instruments is noteworthy, and can be used to improve the detection possibility of weak seismic events.

There are also a number of methods to process the recorded waveform traces in order to extract very weak signals. This will be further discussed in a subsequent presentation, so I will just briefly mention that the most important techniques are to perform filtering of the traces in order to extract the signal frequencies of most interest, and to combine data from an array of instruments by applying an "antenna" principle.

5. Location of seismic events

The location of a seismic event consists of determining the geographical coordinates and the depth of the source.

To obtain precise location estimates, it is necessary to have data from a network of seismic stations which is well distributed around the source. The location procedure itself is simple in principle, and is usually based on observing the arrival time of the P-wave energy at each of the stations. These times can differ by several minutes,

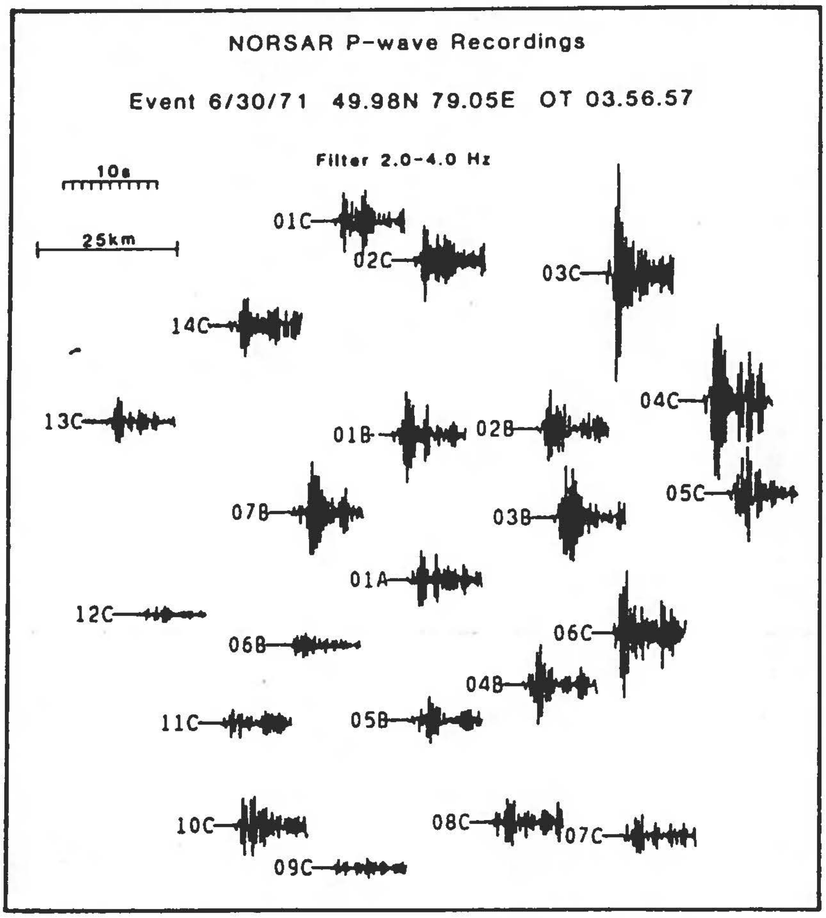


Fig. 4 P-wave recordings at 22 NORSAR instruments for an underground explosion at Semipalatinsk. The traces have been plotted corresponding to the geographical position of the instruments. Note the large variation in signal strength (a factor of 20) across the 100 km aperture of NORSAR.

depending on the distance from the source. Thus, if a sufficient number of observations is available (at least 4, preferably many more), one can calculate the source position that best fits the arrival time data.

Existing global networks can typically determine the event location to within a few tens of kilometers accuracy for well-recorded events. However, the location becomes much more uncertain for small events, where only a few stations detect. There are of course possibilities of improving this performance. For example, if stations close to the event are available, better accuracy is achieved. A "joint location procedure" can be applied if several events have been detected from the same area. The depth estimate of the source can be improved if seismic waves reflected from the surface (so-called depth phases) can be found on the recorded waveforms. Other secondary seismic phases can also be valuable in improving location accuracy.

6. Identification of seismic events

To properly identify a seismic event as either an earthquake or an underground explosion is probably the most difficult aspect of seismic verification. The identification must of course be based on the differences in the physical mechanisms of the two types of source processes, which are schematically shown in Figure 5. While the explosion produces a very simple outward pressure pulse, the earthquake source is much more complex, and produces significant shear energy when slippage along a fault occurs.

In consequence, the relative generation of P-wave and surface wave energy is very different for the two types of events, as shown in Figure 6. This figure is based on NORSAR recordings of an underground nuclear explosion and an earthquake both about 4000 kilometers away, and illustrates that it is possible, in many cases, to conclusively determine the type of source based upon the character of the seismic recordings.

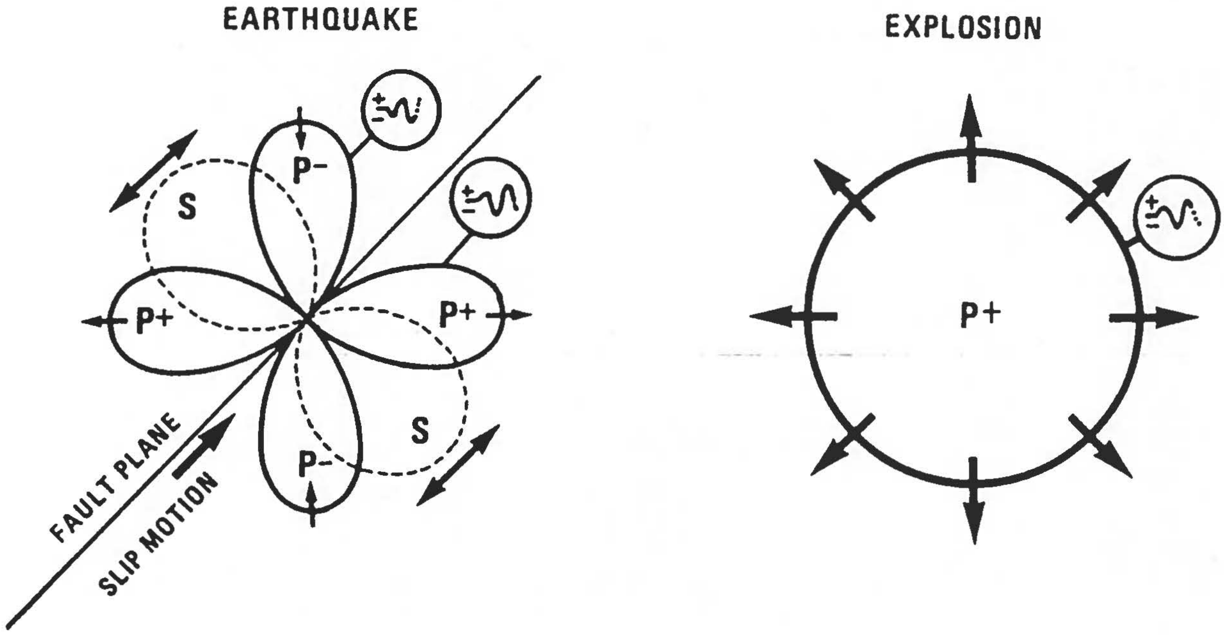


Fig. 5 Earthquakes and underground explosions have different source mechanisms as illustrated in this figure. Earthquakes involve shear motion along a fault plane, while explosions are compressional sources of energy, radiating P-waves with spherical symmetry.

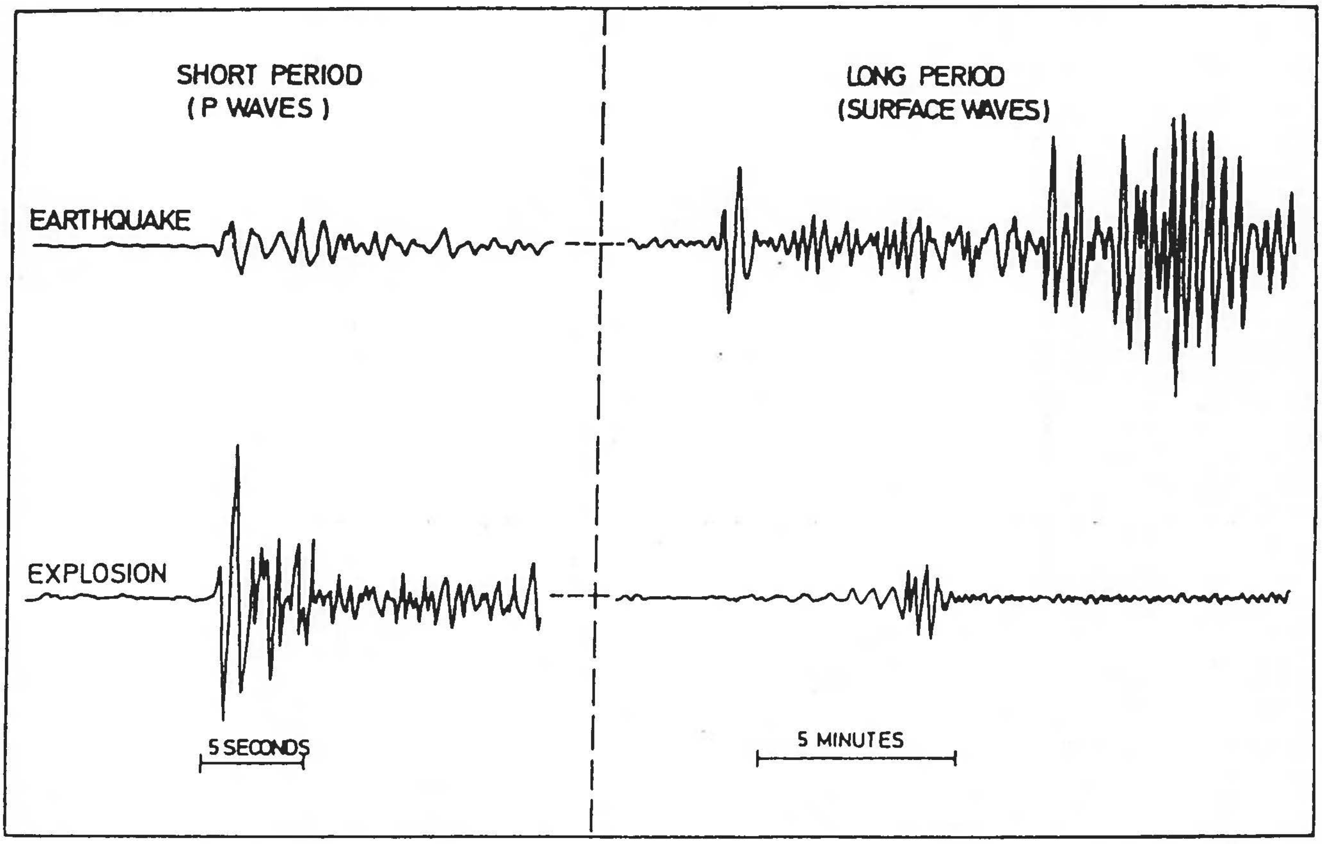


Fig. 6 Recorded signals of explosions and earthquakes have different characteristics features. Note in particular the much stronger surface wave energy relative to that of the P wave for the earthquake.

As is the case also with detection and location, the real problem in identification appears with small seismic events. There is generally little difficulty in correctly identifying well-coupled underground explosions with yields of say 10 kilotons or more. However, in a CTBT environment, one must also consider much smaller events, or explosions which might be set off in a medium with low coupling efficiency, such as large underground cavities. I will briefly return to this point later.

7. The CD Seismic Experts Group

Most of you are familiar with the Seismic Experts Group of the Conference on Disarmament, which has conducted its work on issues related to seismological verification since 1976. This *Ad Hoc* Group has so far submitted three comprehensive reports (CCD/558, CD/43 and CD/448), describing how a global system could be established to facilitate CTBT verification. The Group is currently engaged in evaluating the results from a large-scale technical test of seismic data exchange, which took place in the fall of 1984.

7.1 The proposed global system

I shall now briefly outline the structure of the global system proposed by the CD experts group. This co-operative international effort would have three main elements:

(i) A systematic improvement in the observations reported from more than 50 seismological observatories around the globe.

(ii) An international exchange of these data over the Global Telecommunications System (GTS) of the World Meteorological Organization, or other agreed communications channels.

(iii) Processing of data at special International Data Centers for the use of participant states.

7.2 Selection of seismograph stations for the global network

The Ad Hoc group considered that a suitable global network should comprise around fifty existing or planned seismic observatories, and considered several alternatives in this regard. An example of such a network (Network III) is shown in Figure 7. This network was judged by the Group to be the best one based on available information on existing and planned stations.

7.3 Data extraction at the stations

The Group's recommendations are summarized as follows:

(i) Data are to be reported from each station in standard form in two levels:

Level I: Routine reporting, with minimum delay, of basic parameters of detected seismic signals

Level II: Data transmitted as response to requests for additional information, mainly waveforms for events of particular interest.

(ii) Compared to current seismological practice, increased emphasis is laid on parameters relevant to event identification.

(iii) Strict operational requirements are set forth as to scope, consistency, reliability and promptness in the reporting.

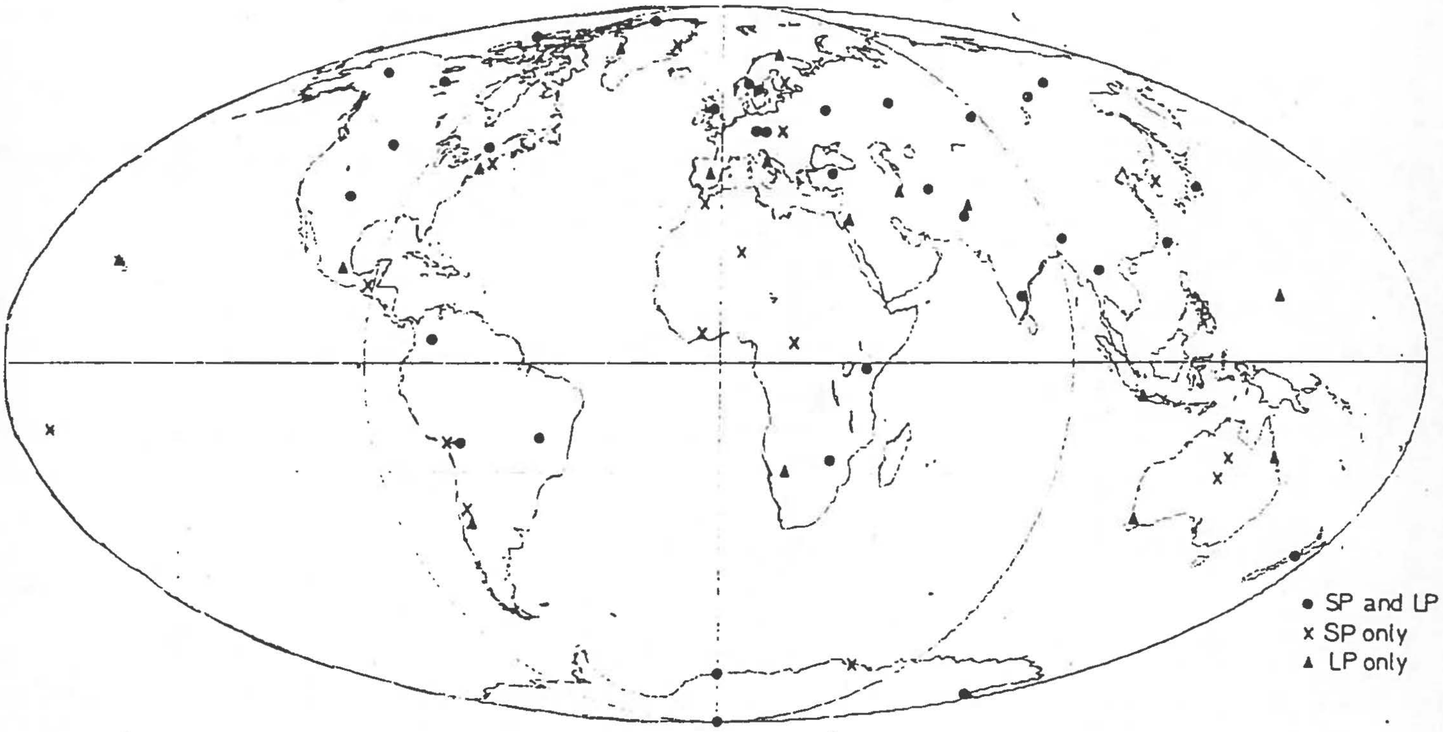


Fig. 7 Map showing the proposed station distribution of the global network (Network III) proposed by the CD *Ad Hoc* Group.

The procedures to be applied for detection, location and evaluation of magnitude and depth of seismic events would follow practice now standard at existing international seismological centers.

7.4 International Data Centers

The Ad Hoc group considered that special International Data Centers (IDCs) should be established for the global network. In order to achieve a reliability acceptable to all, it was proposed that more than one standardized international center be established, each equipped with equivalent hardware and software and performing equivalent processing functions.

The main tasks of the IDCs would be:

(i) to receive data of Levels I and II from the world network of seismic stations via the authorized Government facility of each State

(ii) to apply agreed analysis procedures to available data for the estimation of the origin time, location, magnitude and depth of seismic events

(iii) to associate reported identification parameters with these events

(iv) to distribute in accordance with defined procedures and without interpretation of identification parameters, compilations of the complete results of these analyses

(v) to act as an archive for reported data and results of analysis on those data.

A schematic illustration of the data flow between stations and International Data Centers is shown in Figure 8.

7.5 Projected capabilities of the global system

The Ad Hoc group evaluated in CCD/558 the projected detection and location capabilities of the proposed global system. The estimated detection capabilities are shown in Figure 9. It can be noted that the system is expected to detect seismic events down to body-wave magnitude 4.0 over much of the northern hemisphere, whereas the capability is somewhat poorer in the southern hemisphere.

The estimated location capability, shown in Figure 10 for magnitude 5 events, illustrates that the location accuracy is about 10-20 km in much of the northern hemisphere, but again somewhat worse in the southern hemisphere.

The Ad Hoc group has repeatedly emphasized the need for more high-quality seismic stations in the southern hemisphere, especially in Africa and South America. I would like to use this opportunity to stress this particular point, which is of fundamental importance when looking toward a global verification system.

The Group has also recognized that there is a need to develop methods for more efficient exchange of seismic data, especially Level II data, by the use of modern telecommunications technology. This point will be further stressed during this Workshop.

It is worth noting that the processing load associated with a global system will be substantial, since more than ten thousand seismic events might be detected per year. To provide detailed analysis at the IDCs of all of these reportings will make it necessary to develop improved methods for automatic data handling at these centers.

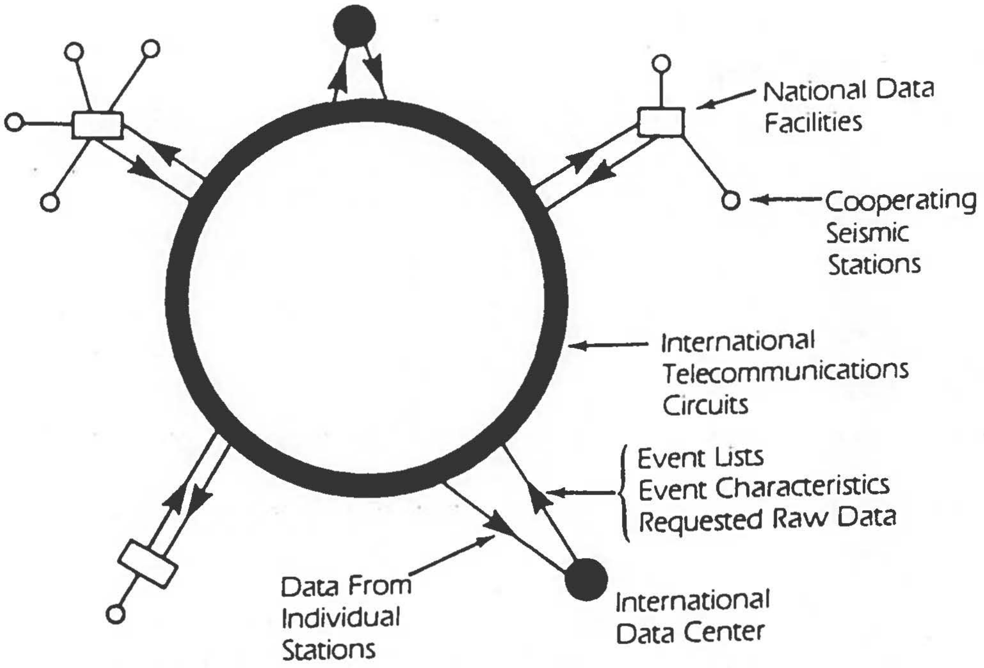


Fig. 8 Schematic illustration of the data flow in the global system of the CD *Ad Hoc* Group.

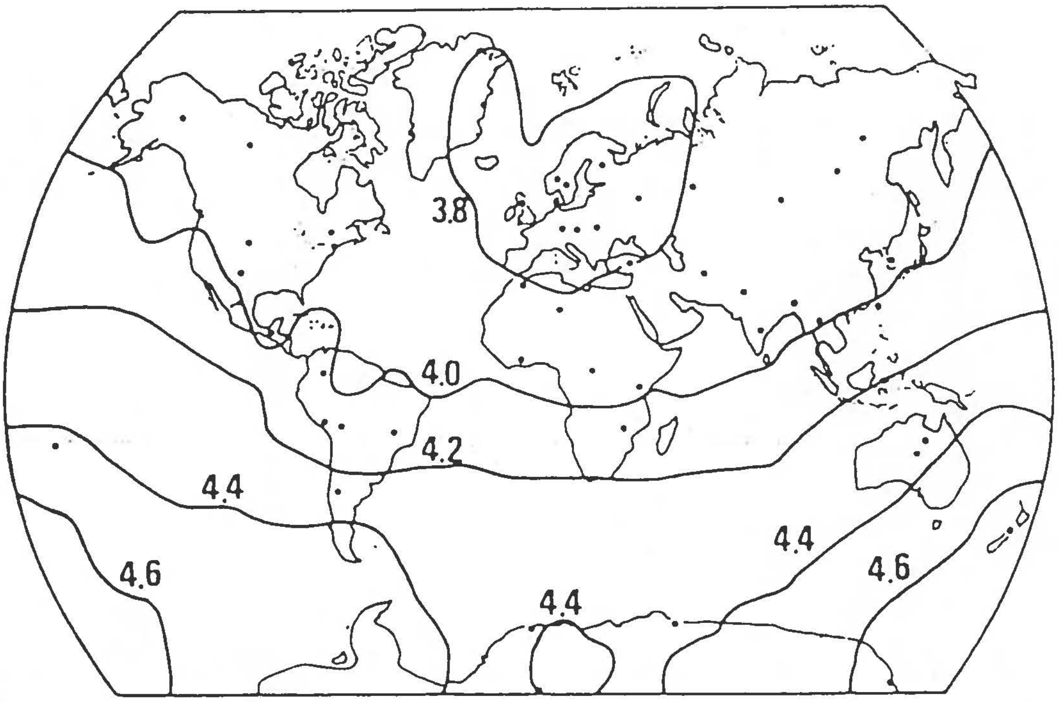


Fig. 9 Estimated short period P-wave detection capability for a hypothetical network of 50 stations proposed by the CD *Ad Hoc* Group (reference CCD/558). The contours represent m_b values for events that would be detected at four or more stations with 90 per cent confidence. The stations of the network are marked as points on the map.

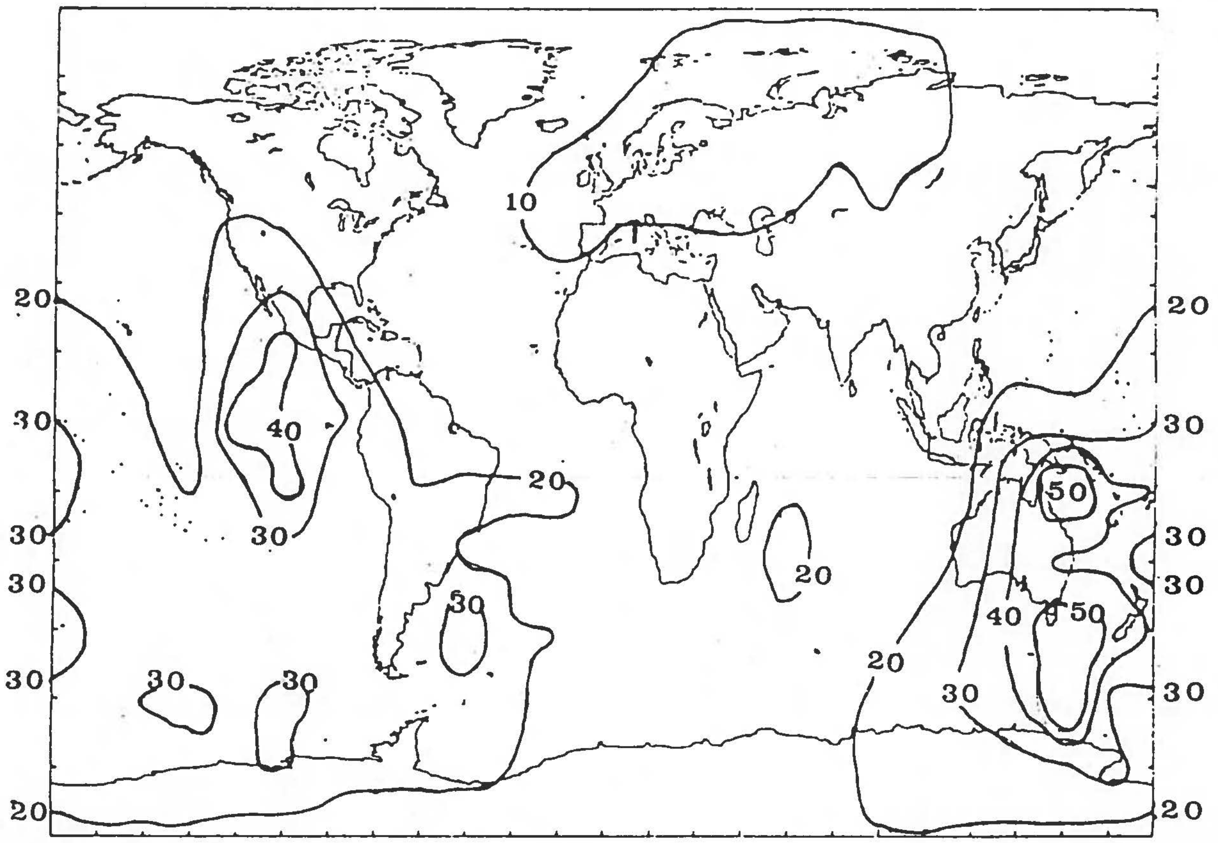


Fig. 10 Estimated location accuracy for shallow seismic events of m_b 5.0 for the global network of the CD *Ad Hoc* Group. The contours represent the error limits in kilometers at a 95 per cent confidence level. Note that these error limits would increase for smaller events.

8. Organizing a CTBT verification system

A CTBT verification system is most likely to comprise three principal elements: i) National Technical Means, ii) On-site Inspection and iii) International Seismic Data Exchange.

8.1 National Technical Means

National Technical Means of verification is usually defined as including any relevant technical system located outside the country under surveillance. Some elements, like seismic stations, special-purpose satellites, etc., are controlled by a single country. Other elements may be negotiated as part of the treaty. Examples of this are provisions for in-country local seismic networks and access to local geological and geophysical data.

8.2 On Site Inspection

The concept of on-site inspection in the case of an ambiguous seismic event reflects a need for more conclusive evidence than provided by seismic recording. Principal techniques of investigation would be radiological sampling and the monitoring of local seismic activity. The need for, and extent of, on-site inspection has been a somewhat controversial issue over the years, but it is noteworthy that an agreement in principle in this regard was reached during the mentioned trilateral negotiations.

8.3 International Seismic Data Exchange (ISDE)

The basis for the ISDE would be operation of a global seismic system along the lines proposed by CD's *Ad Hoc* Group. ISDE is not specifically addressed in the TTB and the PNE treaties, but would constitute a vital part of CTBT verification, as also recognized in the aforementioned trilateral negotiations.

9. Discussion

A verification system for a CTBT must be able to ensure, at a poltically acceptable level, compliance with the agreements and to provide a credible deterrence against potential violations. An important function of such a system will be to build confidence that a treaty is adhered to through extensive international consultation and co-operation.

No realistic seismic verification system will be able to ensure verification of compliance with 100 per cent certainty. Therefore, such a system must contribute to confidence building by minimizing the number of natural earthquakes and man-made non-nuclear events (e.g., chemical explosions) that remain unidentified. The statistical uncertainties associated with detectability levels, explosive coupling efficiency and seismic wave propagation as discussed earlier, make it difficult to give very accurate assessments of the capabilities of a seismic verification system. On the other hand, these same uncertainties are of significant deterrence value, since it will be unknown in advance whether such factors might combine to give a detection by the network of a small clandestine explosion which in theory should be below the average network threshold.

In the following we will address two basic questions concerning CTBT verification by seismic means: (i) what are the necessary verification capabilities and (ii) what are the actual or projected capabilities of envisaged seismic verification systems.

9.1 Necessary verification capabilities

Specifying the necessary verification capabilities for a CTBT is clearly not a seismological problem and is besides difficult to quantify in seismological terms since seismic verification thresholds are not related to yield in a simple manner. However, some critical aspects of this problem will be briefly discussed. For example, since no seismic CTBT verification system can assure absolutely detection of a potential treaty violation, the question of acceptable risk arises. Simply stated: below what yield will signatories to a CTBT be prepared to accept that another party might conduct one or more clandestine tests that might go undetected?

In many scientific investigations, a yield of 1 kiloton is taken as a standard for the size of tests that should be verifiable by a seismic monitoring system. Since the verification problem is probabilistic in nature, the implicit assumption is often made that such a verification capability should be ensured at a 90 per cent confidence level. Others argue that, e.g., a 30 per cent probability of detection would suffice in providing deterrence against clandestine testing. Clearly, such different assumptions would lead to different perceptions of the capabilities of a given verification system.

In seismological terms, a 1 kiloton explosion conducted underground in hard rock corresponds roughly to an event magnitude (m_b) of 4.0. If such a test is carried out in a less competent medium, such as dry, porous alluvium, the m_b value could be in the range 3.0-3.5. In the extreme, theoretical studies have indicated that a 1 kiloton "decoupled" explosion, i.e., conducted in a large underground cavity, could produce seismic signals corresponding to m_b well below 3.0. However, it must also be noted that the decoupling effect might be less severe at high signal frequencies, thus at least partly compensating for the loss in detection possibility.

9.2 Projected verification capabilities

There is no general agreement among scientists on this issue. Many of the differences stem from insufficient calibration data, especially for yield estimation, and different analysis procedures. A classical example of the difficulties is the controversy over whether the TTBT upper threshold of 150 Kton has been exceeded since 1976. Similar problems are encountered when assessing verification capabilities of a hypothetical CTBT monitoring system, e.g., the information available is not adequate as regards seismic noise levels, wave propagation efficiencies, local geological conditions, etc.

The projected 90 per cent detection capabilities of the CD Ad Hoc Group's global seismic network are close to $m_b \sim 4.0$ (roughly equivalent to 1 Kton yield in hard rock) in much of the northern hemisphere. The limiting factor for the sensitivity of this network is principally the relatively large distance separation between constituting stations - it is essentially based on teleseismic event detection. Although the network may be modified by relatively minor improvements to lower its detection threshold to $m_b \sim 3.5$-3.8, the network will not by itself be sufficient to guarantee detection of all seismic events of potential interest.

Thus, in order to ensure adequate verification capabilities, the need for establishing internal networks of stations within the territories of treaty parties has been duly recognized in various CTBT negotiations fora. Such networks would provide much improved detection and location capabilities at local and regional distances. Studies of hypothetical networks indicate that for selected regions the event detection capabilities would be at $m_b \sim 3.0$ and even down to $m_b \sim 2.5$ in certain areas. It should, however, be noted that there are differences of opinion among experts regarding the above capabilities, and this is currently an area of active research.

The projected verification capabilities of internal seismic stations are based on certain assumptions regarding local geology and seismic wave propagation within continental interiors. In the past, the potential of high-frequency (3-20 Hz) wave propagation efficiency has not been fully exploited due to lack of extensive experimental data. An illustrative example of more recent research is studies of recordings from the newly established regional array in Norway (NORESS), which have demonstrated that event detection is possible well below $m_b \sim 3.0$ at distances up to 1500 km. These results will be further discussed in the course of this Workshop.

Many recent scientific investigations have addressed the problems of detecting clandestine tests conducted under so-called "evasion scenarios". The "decoupling" technique, i.e., firing nuclear devices in large underground cavities, thereby strongly muffling the generated seismic signal (particularly at low frequencies) is often considered to be the most serious evasion possibility. Another variant of this scheme is to perform tests in geological environments like alluvium, which are characterized by relatively high seismic signal absorption.

Other potential evasion schemes which have been discussed are to perform tests immediately after very large earthquakes, to test in areas with very high earthquake activity, and to combine chemical and nuclear explosions. The feature in common for these evasion measures is that of distorting the nuclear test-generated seismic signals by literally adding them to seismic signals from a different type of event. The practicality of such evasion measures for a weapons test program point of view is of course debatable, and any evasion scheme would carry a risk of detection which would be a deterring factor. Nevertheless, to obtain effective measures against evasion still remains an important problem in seismic verification.

10. Concluding remarks

The conclusions regarding the current status of the verification issues discussed in this paper can be summarized as follows:

- Substantial technical progress has been achieved during the last few years in seismological verification of a comprehensive nuclear test ban.

- It is essential to establish a global seismological network as proposed by the *Ad Hoc* Group of Scientific Experts to Consider International Co-operative Measures to Detect and Identify Seismic Events. Such a network should secure international data exchange and be based on the most modern technology available at the time of its establishment.

- Some technical problems still remain to be solved. These problems concern in particular detection and identification of very low-yield explosions, and also explosions that are conducted in an environment that produces very weak signals (e.g., underground cavities). The reduced seismic detection possibilities immediately after occurrence of large earthquakes is also a problem that needs further study.

SEISMOLOGICAL FACILITIES IN NORWAY

by

Svein Mykkeltveit, Senior Scientist, Norwegian Seismic Array

1. Introduction

The purpose of this presentation is to give an overview of the NORSAR and NORESS array systems, which form some of the most advanced seismological facilities in existence in the world today.

I will first give some of the historical background for the developments in Norway and then proceed with a brief technical description of the field installations and the data transmission. The automatic analysis of data will be addressed in some detail, and I will include a description of how the systems are being monitored for early detection of possible system malfunction. Next, an evaluation will be offered of array capabilities, and finally examples will be given of seismological research accomplishments at our institution.

2. Historical background for the developments in Norway

The establishment of the large Norwegian Seismic Array (NORSAR) dates back to the signing in 1968 of a Government-to-Government agreement between the United States and Norway concerning seismological research and development. NORSAR construction was completed in 1970. The array has since been in continuous operation and has so far recorded about 100,000 earthquakes worldwide besides reporting more than 500 presumed underground nuclear explosions. NORSAR produces a monthly summary of recorded seismic events, which is distributed to seismological agencies in more than 25 countries. All data from the array are openly available to scientists from all countries.

The NORSAR array can be considered a second-generation large array in that advantage was taken of the experience in design, construction and operation of similar systems during the early and mid 1960s. In fact, the NORSAR array remains today one of the world's largest and most advanced seismological observatories.

A new dimension was added to the seismological research in Norway through the installation in 1984/85 of a new small-aperture array, termed NORESS. The NORESS array with seismometers distributed over an area of only 3 km diameter is designed for optimum detection and location of seismic events that occur within 3000 km of the array, whereas NORSAR is a "teleseismic" array, with optimum performance for events at distances in the range 3000 - 10,000 km. The NORESS array was constructed as a joint undertaking between the U.S. and Norwegian governments, and utilizes recent technological advances in all design aspects. Like NORSAR, NORESS data are openly available to the international seismological community.

Besides the operation of the two arrays and the involvement in test ban verification research, NORSAR research efforts also comprise more general seismological problems, in particular the application of seismic techniques in exploration for oil, gas and ore resources. Research is also being conducted in assessing earthquake hazard for vital industrial installations, such as nuclear power plants, large dams and offshore oil platforms and pipelines. The NORSAR observatory is administered by the Royal Norwegian Council for Scientific and Industrial Research (NTNF) and employs presently 25 persons.

3. Field installations and data transmission

The field part associated with any seismological observatory comprises basically one or several seismometers deployed in direct contact with as competent rock as possible and electronic equipment to amplify the recorded signals. If the data analysis facilities are located at a distance from the field installations, equipment for assembling and transmitting the data to the remote center is also part of the field system.

3.1 NORSAR array configuration and field instrumentation

The NORSAR array is located in southeastern Norway and comprised originally 22 subarrays, distributed over an areas of about 100 km in diameter, as shown in Fig. 1. Seven out of the initial 22 subarrays remain operational today. Each subarray has an approximate diameter of 10 km and contains one long-period (LP) and six short-period (SP) seismometers. The long-period seismometers measure ground motion in three directions: vertical, horizontal north-south and horizontal east-west. The short-period seismometers sense the vertical ground motion.

All NORSAR array seismometers are placed in vaults or shallow boreholes with depths ranging from 3 to 15 m. The geology of the NORSAR array siting area is dominated by old (mostly Precambrian age), competent rock and consists mostly of gneisses and granite. This is a

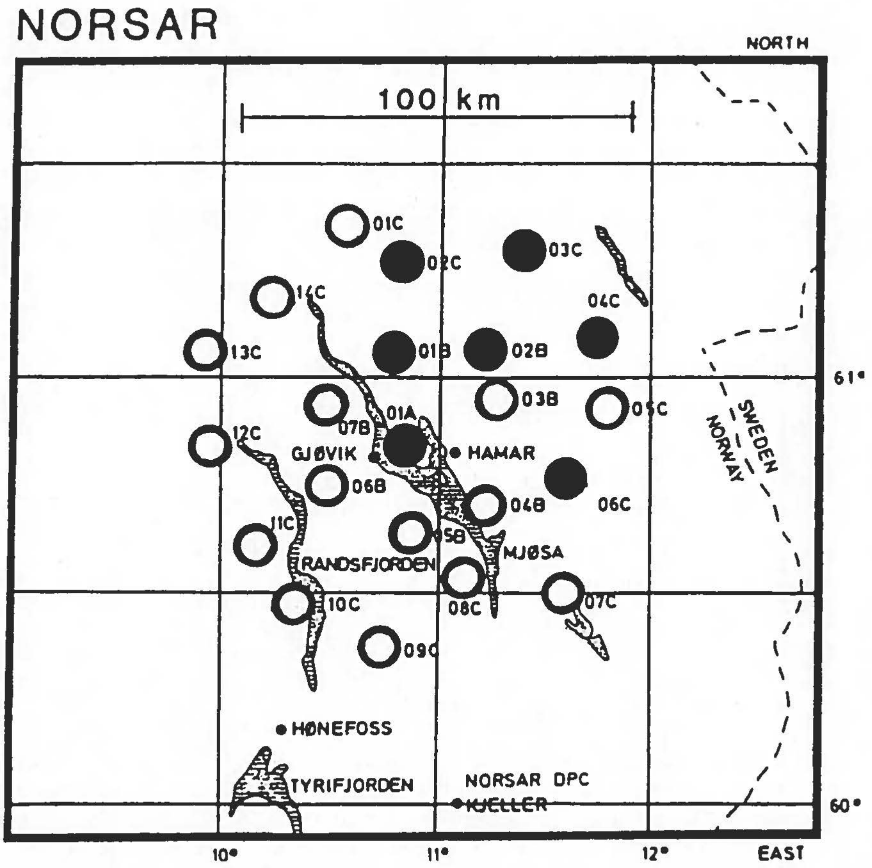


Fig. 1 The Norwegian Seismic Array (NORSAR) is located in southeastern Norway as shown in the figure. The array comprises 22 subarrays, 7 of which are currently in operation (filled circles). Data from the subarrays, which each consists of 9 seismometers, are transmitted to the data center at Kjeller for subsequent analysis.

most favorable environment for deployment of seismometers, as good coupling to hard rock serves to enhance the capability of good signal recording.

From the seismometers the recorded earth motions are transmitted via trenched cables to a Central Terminal Vault (CTV) at the subarray center. The CTV is housing a so-called Short and Long Period Electronic Module (SLEM) which multiplexes and digitizes the 9 seismometer outputs into a single bit stream. The sampling rate is 1 and 20 Hz for LP and SP seismometers, respectively.

3.2 NORESS array configuration and field instrumentation

Unlike the NORSAR array, the NORESS array utilizes a very dense deployment of seismometers. In fact, all 25 NORESS seismometer sites lie within an area of 3 km diameter. In the NORSAR array, the same distance (3 km) represents the typical separation between adjacent seismometers. The geometry of NORESS is shown in Fig. 2. Vertical short-period ground motion is measured at all seismometer sites. In addition, four of the 25 sites are occupied by three-component short-period seismometers. A three-component broadband seismometer is deployed in a 60 m deep borehole at the array center.

Each NORESS seismometers on the four concentric rings is installed in a shallow vault, consisting of a partially buried fiberglass tank sealed to a slab of concrete. This makes a waterproof construction with the seismometer in good contact with the underlying hard rock. Each vault also contains electronics that amplify the signals, convert them to digital form with a sampling rate of 40 Hz and transmit them via trenched fiber optic cables to the central "hub" station at the

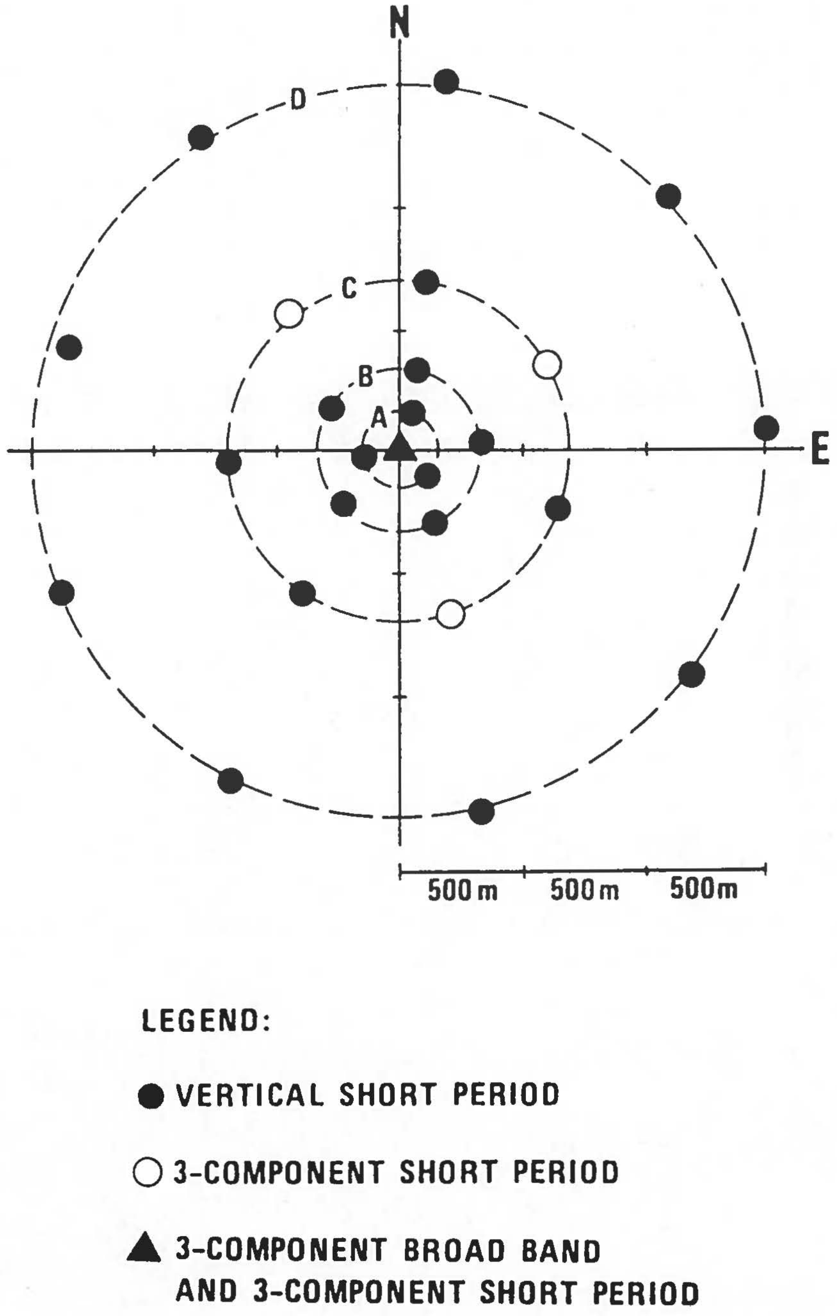


Fig. 2 The Norwegian Regional Array System (NORESS) is located within NORSAR subarray 06C (see Fig. 1). NORESS consists of 25 seismometer sites arranged in concentric circles. Data from NORESS are transmitted to Kjeller for real-time analysis.

station at the center of the array. Optical fibers are used for data transmission, since this means of communication is immune to electrical disturbances from, e.g., nearby power lines and thunderstorms.

The hub station is the operational center of the array. It services all seismometers by providing electric power and timing signals. It also assembles and transmits data from all seismometers. The hub contains equipment that automatically provides calibration commands at regular intervals.

3.3 Data transmission

The block diagram of Fig. 3 shows the NORESS data flow. Communication within the array is, as described in the aforegoing, via buried fiber optic cables. From the hub station, data are transmitted via a land line to the NORESS central computer located at the NORSAR Data Processing Center at Kjeller. Simultaneously, there is communication via satellite to receiving stations at cooperating institutions in the U.S. The Norwegian Telecommunications Administration (NTA) is responsible towards Intelsat for operation of the satellite earth station located at the NORESS hub station. A telephone link to an NTA control center provides NTA with the necessary information on the performance of the earth station.

The data flow from the NORSAR array is in principle similar to that of the NORESS array, with data transmitted via ordinary telephone lines (2400 bauds) from each subarray center to Kjeller, for analysis and permanent storage on magnetic tapes. There is, however, no satellite transmission of data from the NORSAR array directly from the field installation.

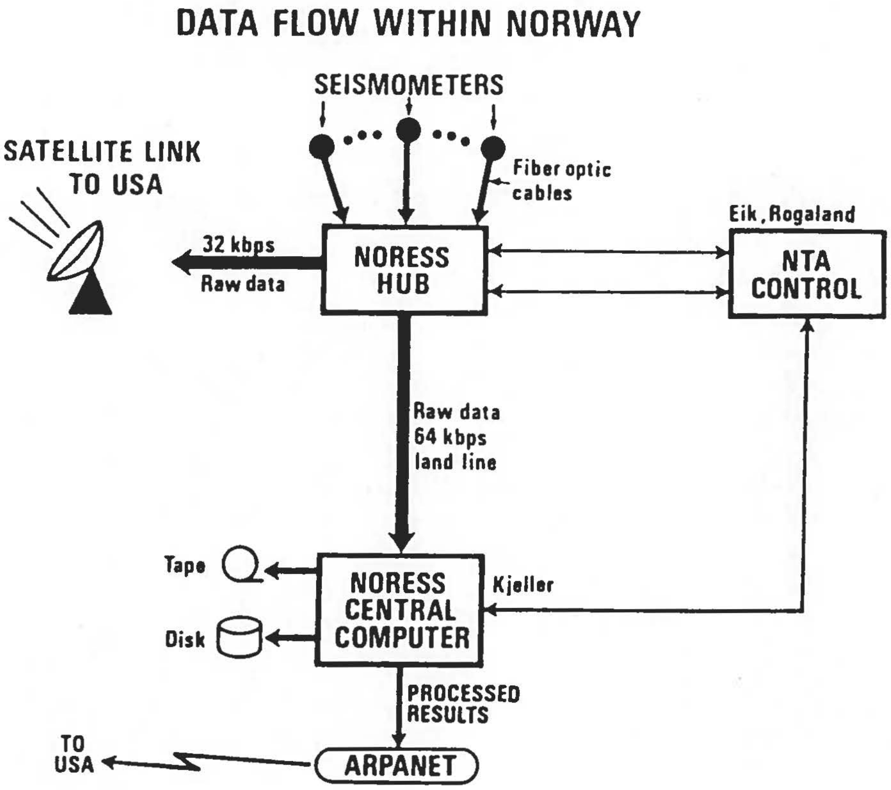


Fig. 3 The figure shows schematically the NORESS data flow with local transmission in the field, transmission by leased telephone lines from the central field site to the Kjeller Data Center, and external exchange of data and processing results.

4. Automated signal detection and processing

Unlike a single seismometer, the distributed nature of arrays like NORSAR and NORESS allows them to locate the source of seismic signals. An array acts like an antenna and is able to focus on and enhance signals from various regions of the earth. Furthermore, a properly designed array is capable of detecting weak signals that in the case of single stations would be completely hidden in the background seismic noise and remain undetected. In the following, the basic techniques that are used to achieve these fundamental objectives of array signal processing will be outlined and a description of how these techniques are utilized in the real-time detection processing at the NORSAR and NORESS arrays will be given. Such techniques are an indispensable part of screening the vast amounts of data generated at seismic arrays.

4.1 Digital filtering for signal enhancement

In addition to and superimposed on signals from specific seismic events, waveform traces contain imprints of the ever-present background noise. This noise results from natural sources for generation of seismic waves like wind, rivers, ocean swells and coastal surfs, and also man-made sources such as vehicle traffic, power plants and industrial activity. These disturbances may be strong enough to obscure signals from weak events totally. However, the period of the ground vibrations caused by noise sources are often different from the period of the interesting seismic signals. A digital filter can then be designed to effectively suppress the seismic energy for all periods outside a specified range. This has been achieved in the example shown in Fig. 4. The three top traces are filtered and the seismic signal is retained. The background noise visible in the bottom three unfiltered traces and corresponding to longer periods of ground motion has been suppressed by the filtering.

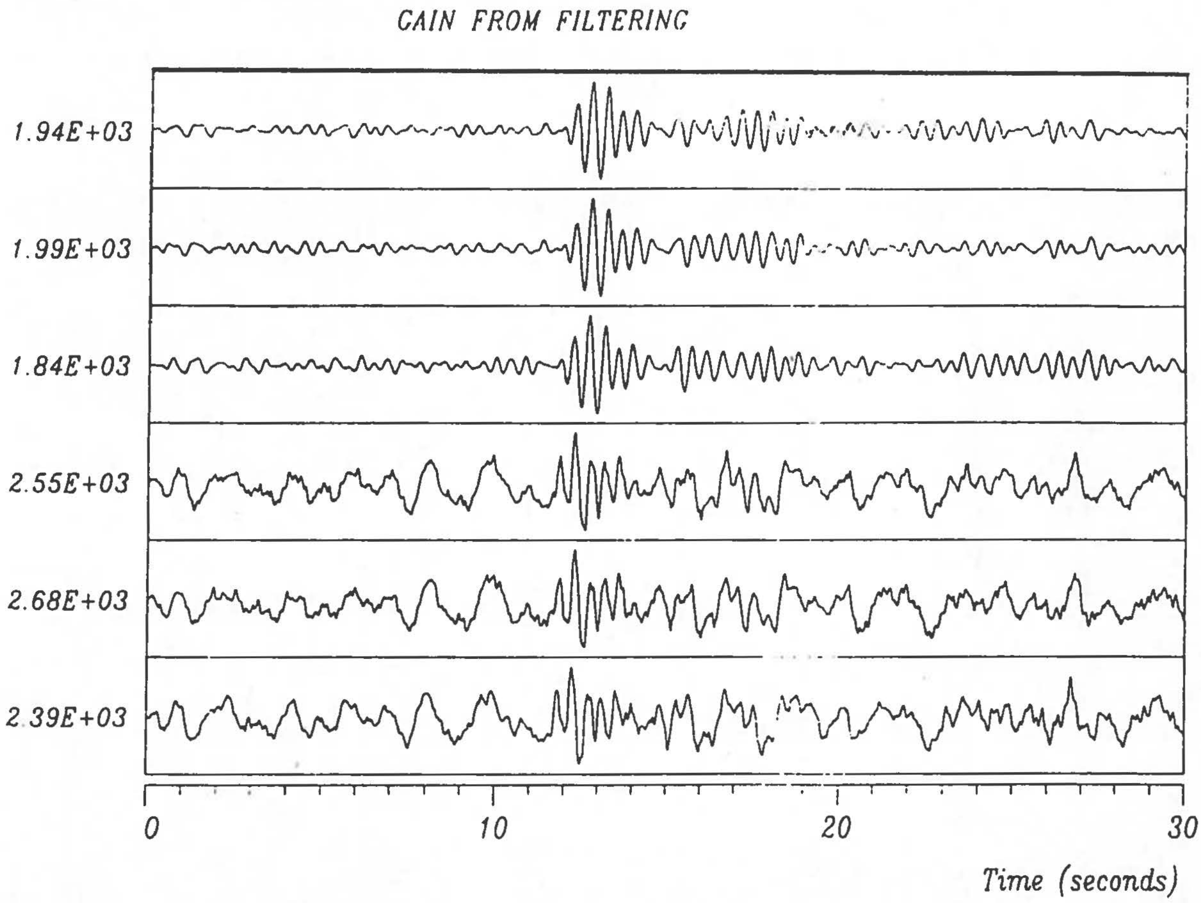


Fig. 4 The figure shows how bandpass filtering can suppress the noise while retaining the signal. The top three traces are filtered, and can be compared to the bottom three traces, plotted here before applying the filter.

4.2 Signal enhancement by beamforming

Beamforming is an important analysis technique for seismic arrays and is usually applied in conjunction with digital filtering. The beamforming technique utilizes the distributed nature of a seismic array, with a number of recordings made at different locations. The success of the beamforming technique relies on the observational evidence that seismic signals are similar as recorded at the various array sites, whereas the background noise tends to produce waveforms that are dissimilar and often cannot be recognized from one sensor to another. The beamforming process consists of two steps: 1) Traces from individual seismometers are time shifted to compensate for the difference in the signal's time of arrival at the various instruments. Such shifts are introduced in order to align the signals. 2) The time-shifted traces are then summed to produce a new trace, which is the array beam. This process causes suppression of the incoherent background noise, whereas the coherent signal is preserved. This is all illustrated in Fig. 5, where the resulting beam is shown as the bottom trace. The figure illustrates that beamforming makes it possible to detect signals that are not visible on individual seismometer records.

4.3 NORSAR array detection and event processing

Extensive use is being made of the signal processing techniques described above in the real-time processing of data from the NORSAR array. About 200 array beams are computed in real time, each with a set of individual sensor time shifts corresponding to the time delay pattern that is expected for signals from a specific geographic location. In this sense, 200 locations distributed in a manner so as to correspond to the most interesting seismic regions worldwide are subject to selected surveillance through the specific beam deployment adopted.

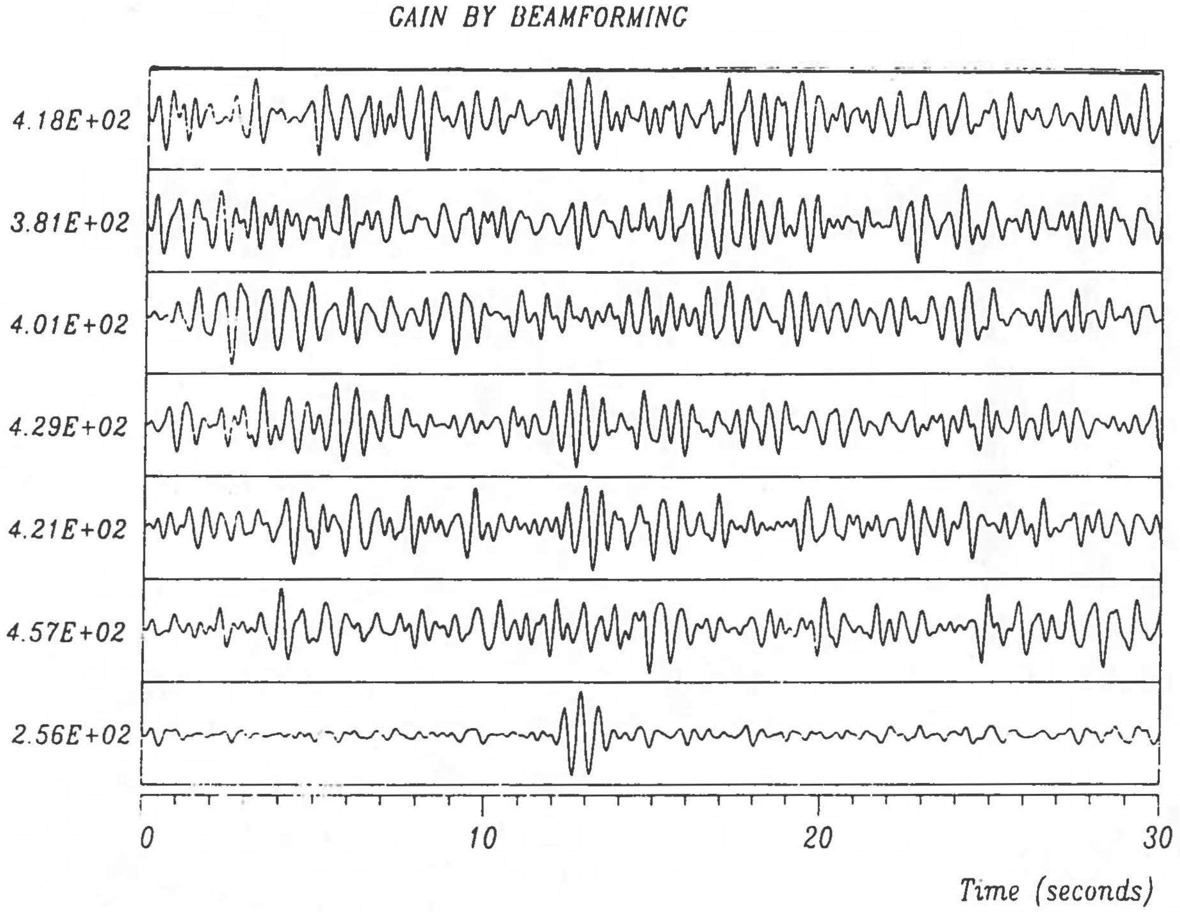


Fig. 5 Illustration of the gain achieved by beamforming. The beam is the bottom trace.

Each of these 200 beams is analyzed in real time, with the purpose of determining whether or not a detection of a seismic event should be declared. The actual detection algorithm performed individually on each array beam is the following (see Fig. 6): the filtered beam is integrated over a sliding time window (length around 2 sec), resulting in a short-term "power" average (STA). A long-term average (LTA) is calculated by a recursive algorithm, which in practice provides a noise estimate based on roughly the past 30 sec of the trace. The ratio STA/LTA is calculated at a specific rate, and whenever it exceeds a predefined threshold a number of successive times, a detection is declared. If several beams show simultaneous detections, the beam with the highest STA is chosen.

With a detection declared in this manner, an event location estimate is achieved implicitly by simply considering which one of the 200 beams detected the signal and to which point on the earth that particular beam is "steered". In this way, a location estimate is achieved simultaneously with beamforming enhancement of the signal for detection purposes. Due to structural inhomogeneities underneath the array, introduction of regionally dependent time delay corrections prior to beamforming is necessary. To ensure adequate coverage of both regional and teleseismic areas, a second type of processing is performed in parallel with the conventional beamforming already described. This process comprises so-called envelope or incoherent beamforming of filtered subarray beams. This method is especially suited to achieve good detection performance for signals with poor coherency across the array. Such signals are usually seen from near events (distance less than 30°), and the envelope beam is in addition highly useful for detecting the high-frequency signals usually observed from explosions.

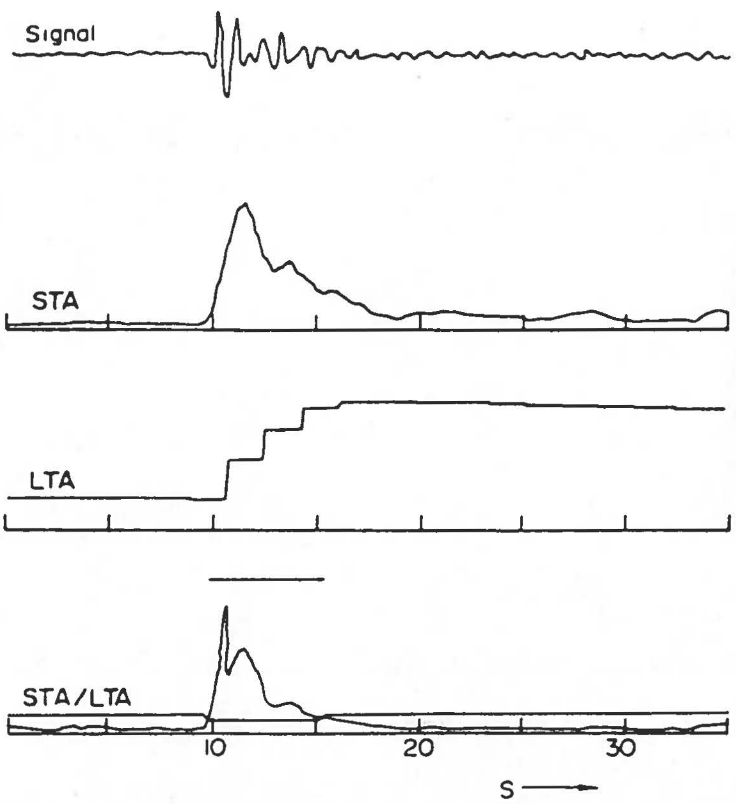


Fig. 6 The figure illustrates the STA/LTA algorithm for detection of seismic signals. The short line above the STA/LTA curve indicates detection state, and the line crossing the curve is the predefined treshold.

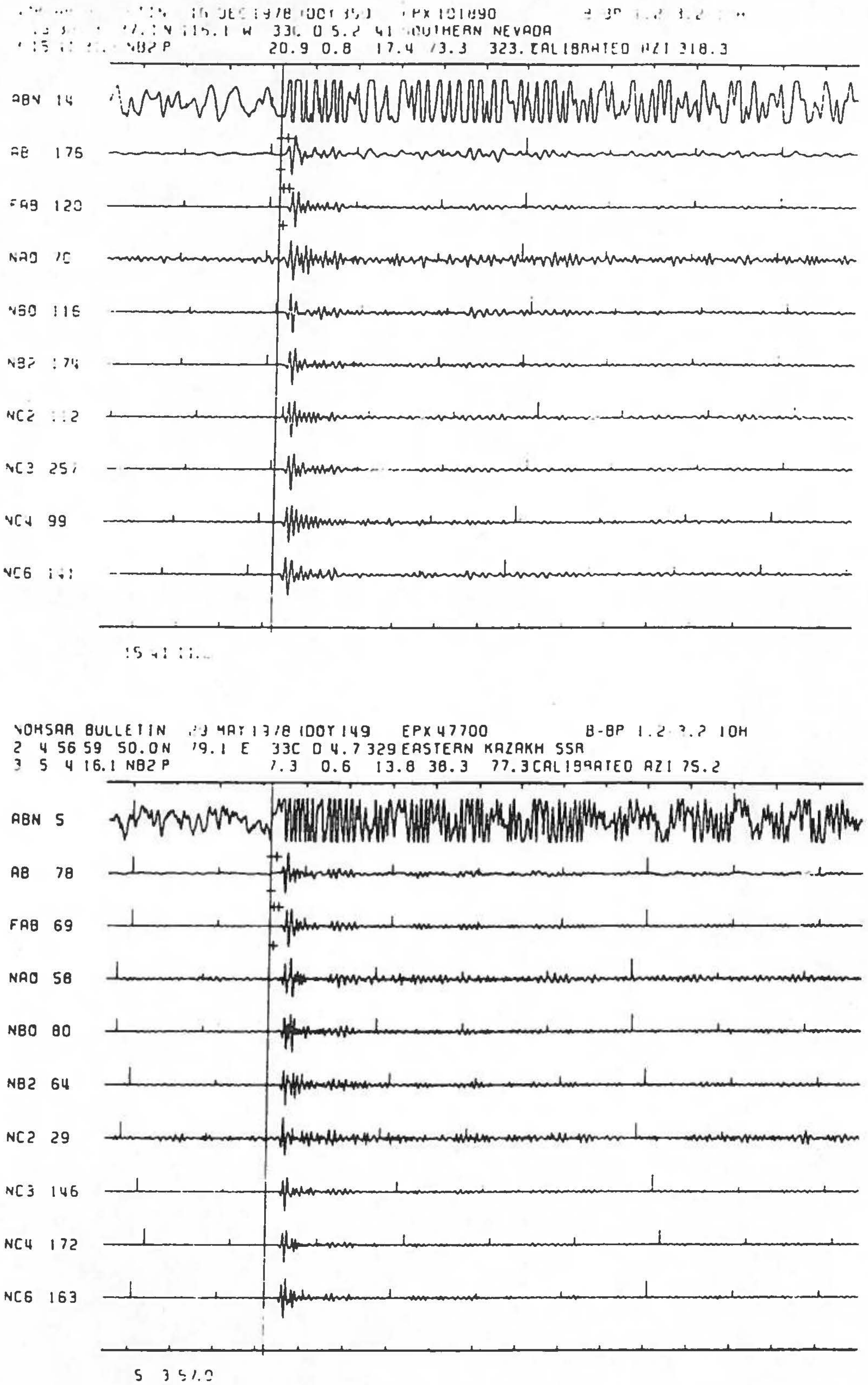
The automatic part of the subsequent event processing consists of picking up and adopting the preliminary location estimate provided by the detection processing, before refining this location through a detailed analysis. Next, the P-wave onset time, amplitude and period based upon the filtered array beam trace are computed, and event origin time is estimated from specially developed tables. Finally, the event magnitude m_b is computed based on the strength of the recorded signal, and corrected for distance from the source. Fig. 7 gives examples of output created by the automatic event processor for two presumed underground nuclear explosions.

The interactive part of the event processing comprises analyst review and in some cases reprocessing of the event to improve upon the estimated source parameters. Currently, in about 30 per cent of the cases, such reprocessing is necessary. While a high degree of automation in the signal analysis at NORSAR has thus been achieved, a completely automatic event processing will need still further refinements. The need for reprocessing is particularly evident for events originating within local and regional distances (up to 3000 km) from the array. This is not surprising, as the NORSAR array was designed for optimum detection of teleseismic events and there are no beams steered to locations at distances less than about 2000 km.

Based on the automatic and interactive NORSAR array event processing, daily and monthly bulletins of seismic events are prepared and distributed to interested parties.

4.4 NORESS array detection and event processing

As already mentioned, the NORSAR array was constructed for optimum performance in the distance range 3000-10,000 km. Furthermore, the sensor spacing was set at around 3 km to ensure decorrelation of the



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[illegible] 16 DEC 1978 IDOY 350   EPX 101890          B-BP 1.2 3.2 [illegible]
[illegible] 7.1 N 115.1 W  33C 0 5.2 41 SOUTHERN NEVADA
[illegible] NB2 P          20.9 0.8  17.4 73.3  323. CALIBRATED AZI 318.3
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NORSAR BULLETIN  29 MAY 1978 IDOY 149   EPX 47700          B-BP 1.2 3.2 10H
2  4 56 59  50.0N  79.1 E  33C 0 4.7 329 EASTERN KAZAKH SSR
3  5  4 16.1 NB2 P         7.3   0.6   13.8 38.3   77.3 CALIBRATED AZI 75.2
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Fig. 7 Examples of output from the NORSAR automatic event processor for two underground nuclear explosions at the Nevada Test Site, USA (top) and at Semipalatinsk, USSR (bottom). For each plot, the three text lines at the top give information on a number of event parameters. Furthermore, 10 signal traces are shown. The top 3 traces are array beams (different scaling and filtering) and the next 7 traces show subarray beams.

seismic noise at 1-2 Hz and at the same time retain signal correlation in the same frequency band. The NORESS array, on the other hand, was designed for optimum detection and location of events occurring within 3000 km of the array. Signals from such events exhibit generally higher frequencies than signals from teleseismic events. This was explicitly taken into account when designing the NORESS array geometry, which is tailored to the characteristics of signals and noise in the frequency range 2-10 Hz, typical of regional seismic signals. Good performance over this wide range of seismic frequencies is assured by placing the seismometers on successively larger rings in exponential progression (see Fig. 2).

The NORESS real-time processing is illustrated schematically in Fig. 8. The detection processor for NORESS data is very similar to what is already described for the NORSAR array: Beams (both conventional and incoherent) are formed to enhance weak signals, the beams are filtered to further suppress the background noise and the STA/LTA ratio is calculated for each beam at a certain rate, for detection of seismic signals above a specified threshold. Beams are now deployed for detection of P, and also the slower S phases observed for events at regional distance.

Once a signal has been detected, it is subject to so-called frequency-wavenumber (F-k) analysis for direct estimation of direction of arrival and wave speed (phase velocity) across the array. This technique amounts to computing a very high number (typically of the order of several thousand) of beams and comparing them to find the one that best enhances the signal.

The actual declaration and location of a regional seismic event relies on a successful association of a P- and S-wave arrival from that event. The wave type (P or S) is determined by the estimated phase velocity (P-velocity typically of the order of 8 km/s and S-velocity approximately 4 km/s), whereas a common direction of arrival

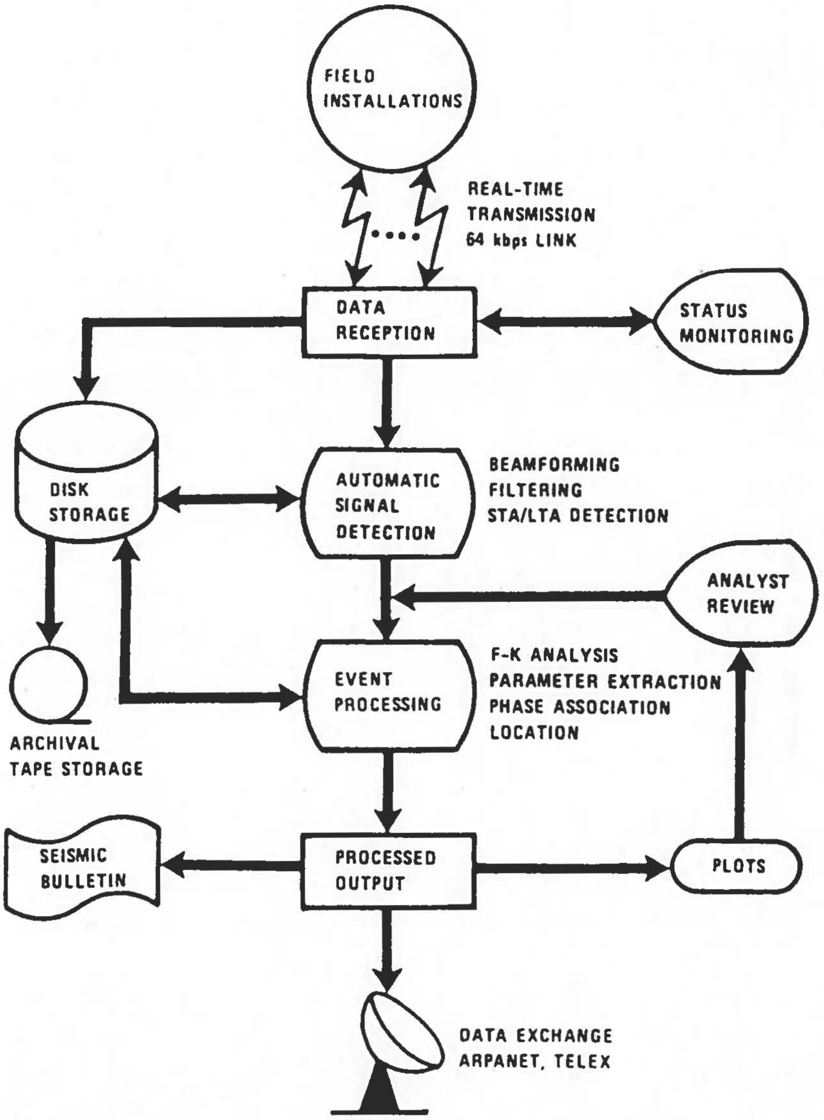


Fig. 8 Flow chart to illustrate the real-time detection processing of data from NORESS.

between the P- and S-phases indicates that the observed signals originate from the same event. The difference in arrival time between the two phases converts directly into an epicentral distance, which together with the estimated direction of arrival determine the event location. Figs. 9 a)-b) show an example of processed output for a local seismic event. In Fig. 9 a), all 25 seismometer traces are shown along with arrows indicating detection of seismic signals. Fig. 9 b) shows results of the F-k analysis, with phase velocities and direction of arrivals for the detected signals. The two distinct phases (P and S) marked by fat arrows in Fig. 9 a) have been combined to give the event location and origin time given on top of Fig. 9 a).

Also for the NORESS array, all data are stored permanently on magnetic tapes, and a seismic bulletin is prepared incorporating the results from the automatic processing and the review by analyst of the processed output.

5. Array status monitoring and control

For technically complex systems such as the NORSAR and NORESS arrays, it is of utmost importance to develop advanced capabilities of monitoring and control of all operational aspects. This is achieved by including a number of state-of-health parameters in the data stream itself and subject these parameters to close surveillance at the data center. In addition, the system itself generates calibration signals that are transmitted to the seismometers, and the resulting response of the instruments to these signals reveals possible instrument malfunction.

For the NORSAR array, there is a two-way data flow between the subarrays and the data center at Kjeller. Special commands are sent from the data center for activating signal generators to test and calibrate seismometers and data transmission lines. Drift of the

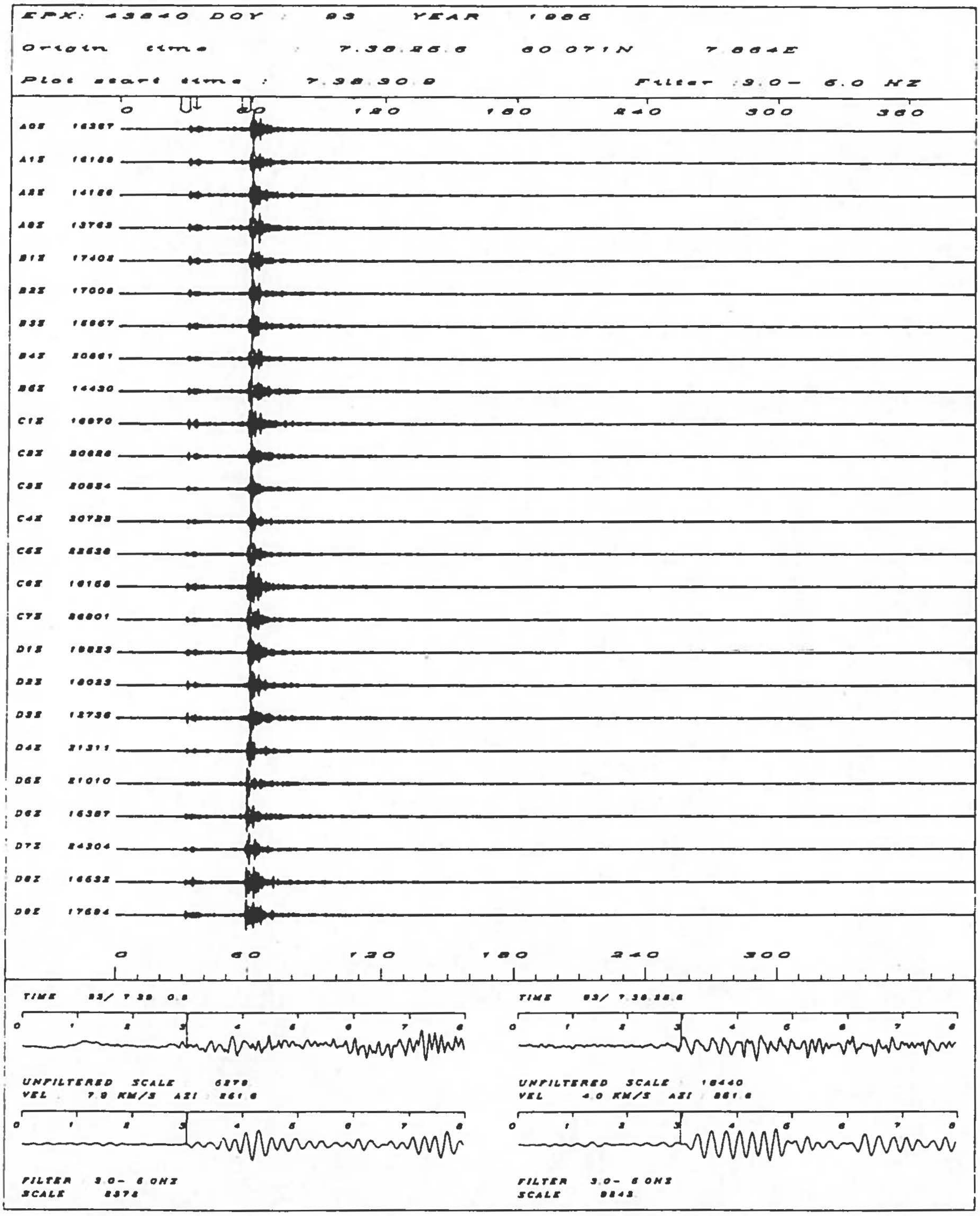


Fig. 9a Example of NORESS automatic processing output for a local seismic event. The panel covers 6.5 minutes of individual bandpass filtered NORESS traces. P and S beams are also shown (bottom part).

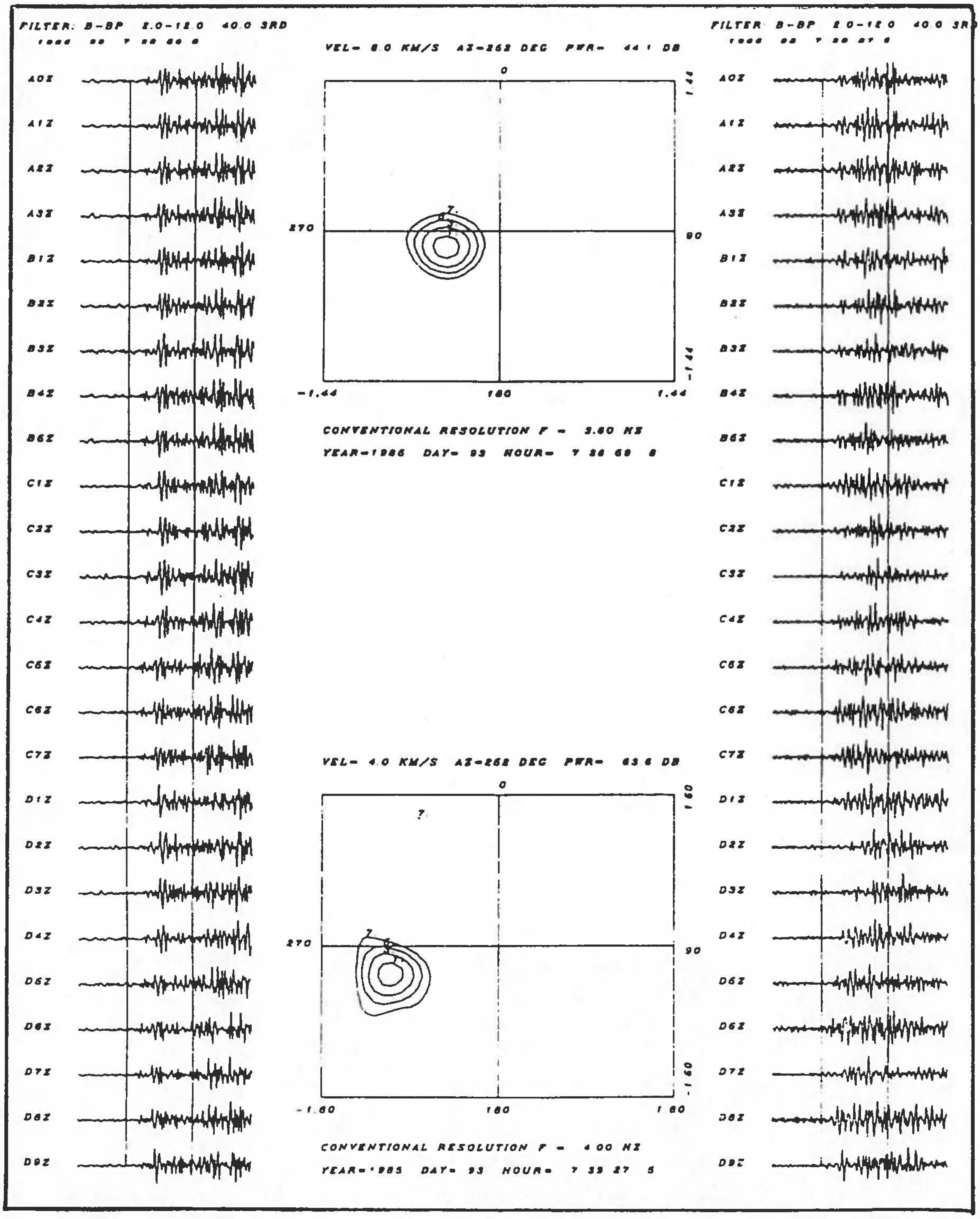
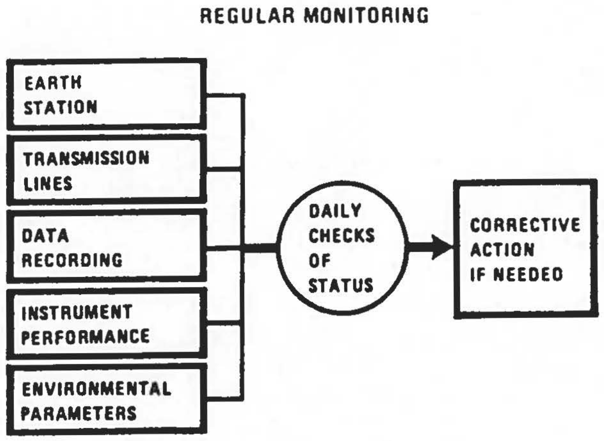


Fig. 9b NORESS automatic analysis results for the event in Fig. 9a. The P-phase (left) and S-phase (right) are shown for all traces in an expanded time scale. F-k solutions are shown for P (top) and Lg (bottom).

long-period seismometer mass position can be corrected remotely by start and stop commands to small electromotors in these instruments. A display enables the operator to check the status of any seismometer or subarray, and 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.

About 20% of the data received from the NORESS array concerns the system's state-of-health, and include environmental parameters like humidity and temperature in all vaults and wind speed and direction at the central hub station. More important, the data carry extensive information on how well the array functions from a technical point of view, and this information enables us to critically survey performance of the field installation, status of transmission lines and recording of data at the data center, all in a fully automated mode. In fact, failure to record data at any time triggers an alarm that reaches the operator on duty. The block diagrams of Fig. 10 give details on system components subject to regular and emergency-type monitoring and actions taken in case of failure of vital array functions. For the NORESS system, instrument calibration signals are generated automatically at regular intervals and instrument responses are recorded and stored on tape, along with all other data. This makes it possible to verify adequate or inadequate instrument functioning at any time in the past. Fig. 11 shows data for a time interval with



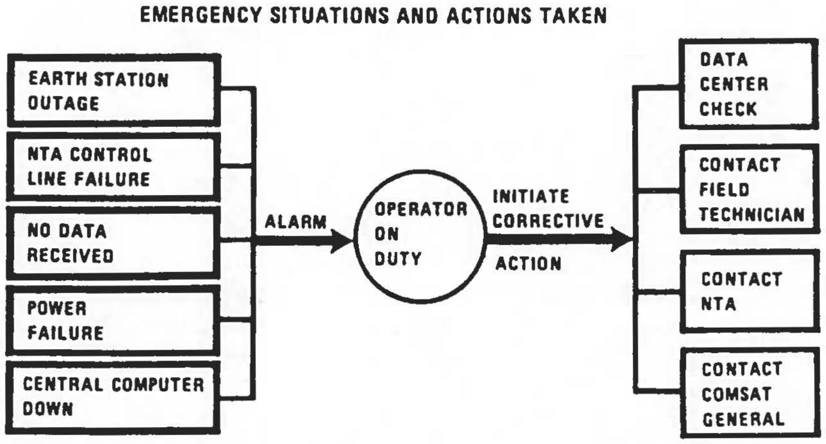


Fig. 10 The block diagrams illustrate how NORESS is subject to regular and emergency-type monitoring. Failure to record data at any time triggers an alarm that reaches the operator on duty.

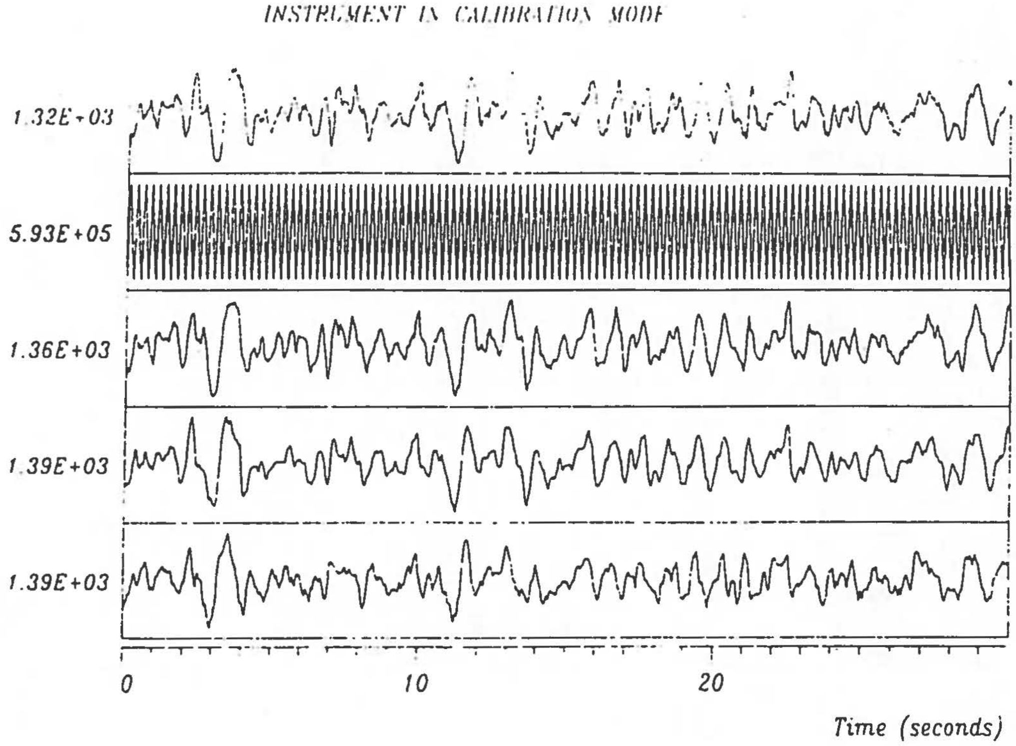


Fig. 11 For NORESS, calibration signals are generated automatically at regular intervals and reveal possible instrument malfunction. The second trace from the top is for an instrument in the calibration mode.

one instrument in the calibration mode, whereas the other instruments record data normally.

It is fair to say that for both the NORSAR and NORESS arrays, the emphasis on generating and analyzing a large amount of state-of-health data is essential in ensuring continued operation and maintaining high data quality.

6. Evaluation of system capabilities

The NORSAR array is situated in a favorable geological environment. Furthermore, many major earthquake zones of the world as well as test sites for underground nuclear explosions are situated at distances within the optimum detection window 3000 - 10,000 km away from the array. All of this contributes to excellent detection capabilities, particularly for most of the northern hemisphere. In fact, for many regions of the world, the NORSAR detection performance is unsurpassed.

More specifically, comprehensive analyses have established that there is a 90% probability for detection by the NORSAR array of a magnitude 4.0 (body wave magnitude m_b) event in the teleseismic distance range 3000 - 10,000 km. The detectability varies from region to region within the teleseismic range, and it is generally better to the east than to the west. This is understood in light of the geological setting: Regions to the east are located on the same lithospheric plate as the NORSAR array, and propagation of seismic waves is generally more efficient for paths that do not cross plate boundaries. Thus, the NORSAR detection capability approaches m_b = 3.0 in many regions within the Eurasian continent.

Experience from the NORSAR array has shown that even a large array cannot routinely locate seismic events with high accuracy. Fig. 12 shows that the median location error for the array (relative to solutions by a global network of single stations) is more than 100 km at teleseismic distances. Array location estimates, although inferior for large magnitude events to those provided by worldwide networks, become increasingly important at low magnitudes. This is because the locating accuracy of global networks, as reported by the appropriate agencies, deteriorates rapidly when only a few stations report an event. In many cases, the NORSAR and other arrays provide locations of events that are below the reporting thresholds of these agencies, and are thus crucial in detecting arrivals that would otherwise have been left unreported.

Turning to the NORESS array, preliminary analysis has given a detection threshold of about m_b = 2.0 - 2.5 at 1500 km epicentral distance. In the distance range up to 1500 km, advantage is taken of the high signal frequencies observed, in combination with the strong decay in the noise level with increasing frequencies. For distances in the range 1500 - 3000 km, large regional variations in detectability are observed. For Eurasia, estimated threshold at these distances range from m_b = 2 to m_b = 3. In the teleseismic range, 3000 - 10,000 km, the detection capability of the NORESS array is as good as that of the NORSAR array for some regions of the world, whereas, for other source regions signal focusing effects underneath NORSAR cause some NORSAR instruments to have up to an order of magnitude stronger signals than NORESS sensors. For such regions, NORESS does not match the NORSAR array detection capability. Also, due to the small aperture of the NORESS array, only a very coarse automatic location of teleseismic events is currently being made.

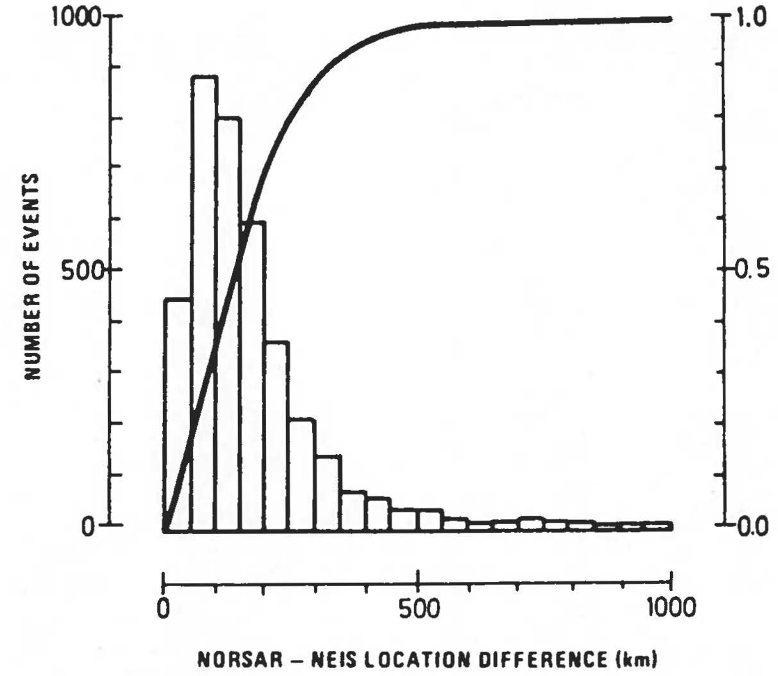


Fig. 12 Incremental and cumulative distribution of epicenter location differences between NORSAR and NEIS (a reporting agency) from January 1973 to March 1975. Only events in the distance range 30° to 90° from NORSAR have been included, and the median location difference is 130 km.

The location accuracy of the NORESS array for regional events is currently being studied. Results are available, however, for a provisional array installatin preceding the current NORESS array. For an array geometry comprising only 6 instruments within an area of 2 km diameter, the location "errors" are illustrated in Fig. 13, which shows differences between locations based on this provisional NORESS array and those derived from the Fennoscandian network of single stations. Median location difference is 30 km, which is of the order of the uncertainty of the Fennoscandian network. The location capability of the current NORESS array will be better than indicated by Fig. 13.

In summary, the two seismological arrays in Norway complement each other and provide event detection and location for events at distances ranging from very local to teleseismic.

7. Seismological research at the NORSAR observatory

Seismological research at NORSAR has focused on many aspects of seismology that are of relevance to the detection and identification of seismic events using our arrays, with the goal of improving upon the array capabilities. This work has resulted in nearly 400 published papers and technical reports over the years, and it is only possible in the present context to mention a few areas where reseach efforts at NORSAR have resulted in significant contributions. An archive counting more than 18,000 magnetic tapes with data from our two arrays is instrumental in conducting this research.

The spatial sampling of the seismic wavefield offered by seismological arrays sheds light on characteristics of seismic wave propagation in

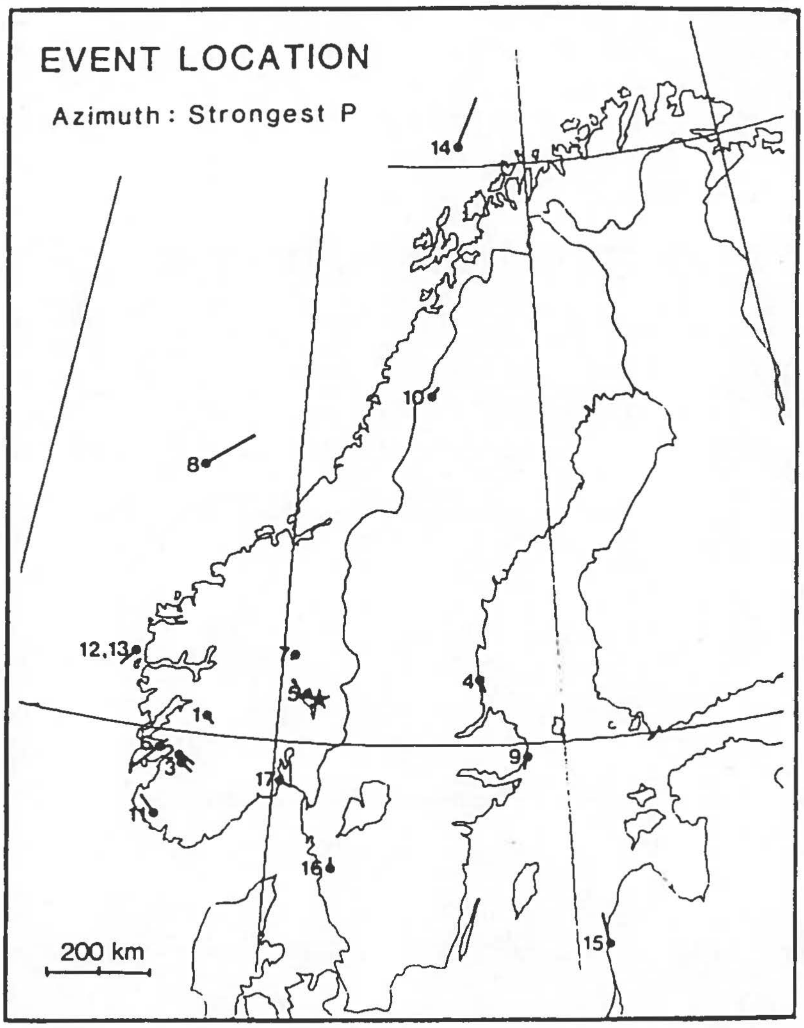


Fig. 13 Location "errors" from a provisional NORESS array for a set of 17 regional events. Filled circles indicate epicenters determined by the Fennoscandian station network, while the tails of the arrows give locations from NORESS processing. The site of the provisional NORESS array is indicated by a star.

general. Such insight regarding properties of the seismic noise field was utilized directly in the recent design of the NORESS array. This has lead to an excellent P-wave detection in the 2 - 4 Hz frequency band, mainly due to very effective noise suppression from destructive interference by the particular geometry chosen for the NORESS array.

P-wave signals sampled by the NORSAR array exhibit waveform distortions and travel-time and amplitude anomalies which are not consistent with the early, rather simplistic seismological concept of homogeneous lithospheric structures. This observation has motivated the development of mathematical modelling and inversion techniques for proper understanding of these observational anomalies in terms of three-dimensional lithospheric/asthenospheric seismic velocity variations. In addition, data from arrays like NORSAR have been used to establish the existence of fairly general features of the earth structure, like several discontinuities in the mantle.

The main practical value of seismic arrays for comprehensive test ban treaty verification lies in the detection and possible identification of low-magnitude events, and the superiority of arrays compared to single stations in this context is evident. Further improvement of the capabilities of our arrays in this respect has been and will remain a main topic of our research programs. Notable contributions so far have been development of methods for improved magnitude estimation and application of autoregressive modelling for discrimination purposes.

8. Concluding remarks

It is our sincere hope that the preceding presentations will contribute to an understanding and appreciation of the role of seismology and seismic arrays in verification of a comprehensive test ban treaty. In particular, we consider that the NORESS developments will provide further insight into the use of small seismic arrays as internal stations placed inside the signatories' territories in a possible future monitoring environment.

The main purpose of the Norwegian Seismic Array will remain to be research and experimentation toward achieving adequate verification of a CTBT. Towards this goal, Norway has aimed at developing the observatory into an international center for research in seismology, and visiting scientists from more than 20 eastern, western and non-aligned countries have conducted research work at our institution. We hope that these cooperative efforts can be further expanded, to the benefit of the seismological community.