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Working Paper

Seismic Verification of a Comprehensive Nuclear Test Ban: Future Directions

1. Introduction

Seismological means of verification would constitute a crucial element in ensuring compliance with a comprehensive nuclear test ban. In recent years, considerable progress has been made in specifying how an international seismic data exchange could be achieved. In particular, the three reports (CCD/558, CD/43 and CD/448) of the Ad Hoc Group of Scientific Experts to Consider International Co-operative Measures to Detect and Identify Seismic Events have provided a valuable contribution in this respect.

Norway has over the years devoted considerable resources to conducting seismological research in areas relevant to CTB verification. The operation of the large-aperture Norwegian Seismic Array (NORSAR) and the associated research activities have formed a key element in these efforts.

This document is a follow-up of two previous working papers (CD/310 of 11 August 1982 and CD/395 of 19 July 1983). It includes a presentation of a new, small-aperture array (NORESS) which is currently under development in Norway and which will incorporate many of the latest technological advances in seismic instrumentation, telecommunication and signal processing techniques.

The present paper also gives an overview over recent efforts to establish methods for rapid international exchange of seismic data under a future CTB, in particular seismic Level II (waveform) data exchange using modern telecommunication technology.

Finally, a review is given of recent research on topics relevant to the detection, location and identification of seismic events. In particular, attention is drawn to some new results which show that the possibilities of detecting seismic signals of very high frequencies are much better than previously assumed. This could have important implications for improved detection of weak seismic events as well as for seismic source identification.

2. The Norwegian Seismic Array (NORSAR)

The NORSAR observatory was established under a co-operative agreement on seismological research between the United States and Norway, and has been in operation since 1970. NORSAR, which is located in south-eastern Norway, is a large aperture seismic array comprising 42 vertical short period and 7 three-component long period seismometers, extending over an area of 60 kilometres in diameter. The array is situated in a favourable geological area, well removed from major earthquake zones, and its event detection capability is excellent for most of the northern hemisphere.

NORSAR, which currently is one of the world's largest seismological observatories, has throughout its 14 years of operation recorded high quality seismic data in digital form for about 70,000 earthquakes and more than 500 presumed nuclear explosions, and has thus provided a data base of great value for seismological research. A monthly summary of recorded seismic events is regularly distributed to seismilogical agencies in 25 countries. All data and research results from NORSAR are openly available to the seismological community.

Norway has attached considerable importance to establishing NORSAR as a research facility open to scientists from all countries, and a number of international co-operative research projects have been carried out over the years.

3. The Norwegian Experimental Regional Array (NORESS)

Under the co-operative research agreement between the United States and Norway, a new experimental small-aperture array named NORESS is currently under construction in Norway. In contrast to NORSAR, which is primarily designed to achieve optimum performance for seismic events in the so-called teleseismic range (distances 3,000-10,000 km), the purpose of NORESS is to develop methods for detection and location of seismic events at so-called local and regional distances (less than 3,000 km). In a CTB environment, stations of this type would be of particular importance in detecting and locating events too weak to be observed at teleseismic distances. However, preliminary results have shown that such small arrays also hold promise in improving teleseismic detection of high frequency signals.

The NORESS development will incorporate the latest technological advances in seismic instrumentation, telecommunication and signal processing techniques. The array will comprise 21 vertical and 4 three-component short period seismometers deployed over an area of 3 km in diameter. In addition, a three-component broadband seismometer will be installed in a borehole at the centre of the array. The data will be converted to digital form at the recording site with transmission via fiber optic cables to the array centre. From this point, the data are to be further transmitted by a wide-bank land line to the NORSAR data centre at Kjeller.

Data from NORESS will be processed in real time at the NORSAR data centre, and stored on magnetic tape for future reference. All data and processed results from NORESS will be made available to the international seismological community. The array is expected to be operational in the fall of 1984.

4. International Seismic Data Exchange

Norway has, through contributions by NORSAR scientists, participated actively in the work of the Ad Hoc Group of Scientific Experts on seismic events from its inception in 1976. A number of technical papers have been submitted by Norway toward the Group's three reports. Norway participated in both of the Ad Hoc Group's trial exchanges of seismic Level I data via the WMO/GTS in 1980 and 1981, and will also take part in the planned 1984 experiment, by contributing NORSAR data.

Norway has taken a special interest in the work of the Ad Hoc Group concerning exchange of seismic Level II (waveform) data. Sponsored by the Norwegian Ministry of Foreign Affairs, NORSAR scientists initiated in 1980 a research project to evaluate how modern telecommunications technology could be used to improve the exchange of such data within a future global CTB verification system. In August 1982 the Norwegian delegation demonstrated for members of the Committee on Disarmement a prototype system developed for this purpose, based on a flexible, inexpensive microprocessor. This prototype has since been developed further, and will eventually include options for handling eight seismometers, real-time signal detection and off-line processing of detected events in the field.

The essence of the system is that both Level I and Level II data would be automatically extracted at the recording site and then temporarily stored. These data can then be retrieved either by a national or international data centre, through the ordinary telephone network or directly via satellite. Emphasis is placed on ensuring nearly real-time access to Level II data since many national investigations reported to the Ad Hoc Group have shown that such data are valuable for improved event analysis at data centres.

In September, 1982 NORSAR invited other seismological observatories to take part in experiments to exchange Level II data through international telecommunications services. Although this has been successfully achieved with several external centres, experience so far has shown that it is essential that national seismological centres contributing to the envisaged global network are equipped with adequate computer facilities. Further efforts to improve this type of data exchange are continuing, not only in Norway, but in many other countries as well.

5. Detection and Location of Seismic Events

At NORSAR, considerable research efforts have been devoted to improving the automatic detection of weak seismic events. It is well known that a seismic array can achieve improved detection capability compared to a single sensor station by combining the signals from individual array elements through a "delay-and-add" procedure known as beamforming. Research conducted at NORSAR has shown that further improvements can be obtained by applying special array processing techniques such as envelope beamforming and by assigning different weights to individual sensors in the beamforming process. Significant results have also been achieved in applying a technique known as high-resolution analysis to separate interfering events.

Because of the large geographical extent of NORSAR, it has been possible to study in detail the spatial variations of signals recorded from a given event. Of particular interest to the detection problem is the signal "focusing" effect that is regularly observed. Thus, for any given source region, particular sites within NORSAR can be found where signal detection is much better than average, and the difference in signal strength across the array often amounts to as much as an order of magnitude. The location of these "good" sites within NORSAR varies with the source region.

This focusing effect has been exploited at NORSAR to optimize detection capability for selected regions, and could possibly be applied in a global network by carefully selecting sites to improve teleseismic coverage of regions of special interest.

An array has the capability to provide initial estimates of the velocity and direction of arrival of incoming signals, and can thus be used for seismic phase determination and to give preliminary estimates of the locations of recorded seismic events. Experience from NORSAR has shown that even a large array cannot routinely provide very accurate location estimates, as the error is usually of the order of 50 kilometres or greater. While this precision is generally inferior to that obtained from a globally distributed network for large events, location estimates from arrays become increasingly important at low magnitudes. This is because the location accuracy of global networks deteriorates rapidly when few stations report an event. In many cases, a sensitive array will provide the only available location estimates, and will thus be instrumental in the search for confirming detections from other stations.

In special cases, arrays can provide location accuracy much better than the average figure. Using NORSAR data, it has been found that information from secondary P-phases observed at distances less than 3,500 km can be used to obtain very precise epicentral distance estimates. Improvements are also possible by utilizing high-frequency signals in conjunction with detailed regional calibration.

Research conducted at NORSAR in preparation for the previously described NORESS array has shown that reliable phase determination and location estimates at short distances can be obtained from an array of very small aperture (diameter 1-3 km). An experiment conducted in this connection gave very small location errors (in many cases less than 10 km) for events within 1,000 km distance from the array. Further improvements should be possible when data from the full NORESS array become available.

6. Identification of Seismic Events

In CCD/558 a number of criteria useful in distinguishing between the signals from earthquakes and underground explosions were listed. A substantial research effort has been carried out at NORSAR both in evaluating these discriminants and in further developments. In particular, attention has been focused on surface wave versus body wave magnitude (M_s:m_b) and on identification criteria based on the observed frequency contents of P-waves.

An important prerequisite for applying many discriminants is to obtain an accurate estimate of the magnitude of a seismic event. Research at NORSAR has demonstrated that event magnitude estimates obtained from seismic networks can be substantially improved by taking into account both the signal level at those stations detecting a given event and the noise level at stations where the signal is too weak to be detected. This is of particular importance for low magnitude events, which of course are of utmost concern in a CTB context.

Methods have also been developed to characterize the P-wave recordings of a seismic event in terms of so-called autoregressive parameter representation. This procedure, which takes into account the character of the entire recorded seismic signal, has given promising results as a discriminant when applied to NORSAR data for seismic events in Eurasia.

Recent studies at NORSAR based upon data from new, high quality instruments have shown that the seismic noise level at high frequencies (up to at least 40 Hz) is much lower than previously assumed, and also that there is significant signal energy for regional events at these frequencies. This could open up new possibilities both in signal detection at regional distances and in seismic source identification using very high frequency signals. These possibilities will be further studied when data from the new NORESS array become available.

7. Future Plans

Some important topics for further research and development have already been outlined in this paper. Future Norwegian research efforts will place particular emphasis on improved detection, location and identification of low magnitude seismic events, especially in conjunction with the NORESS developments. An important part of this is continued efforts in obtaining an improved understanding of the physical processes involved in the release of wave energy from underground explosions and natural earthquakes.

At the same time, further research will be conducted to improve methods for rapid exchange of Level II data in the context of an international seismic data exchange under a future CTB. Of particular importance here is to take advantage of the rapid, on-going developments in computer and telecommunication technology. Coupled with the steadily decreasing cost of data transmission via satellite, these developments will open up new possibilities for improving seismic data exchange under a future treaty.

Norway will continue to encourage and participate in international co-operative research projects, and will also in the future offer the facilities of NORSAR for such undertakings.