Royal Norwegian Council for Scientific and Industrial Research

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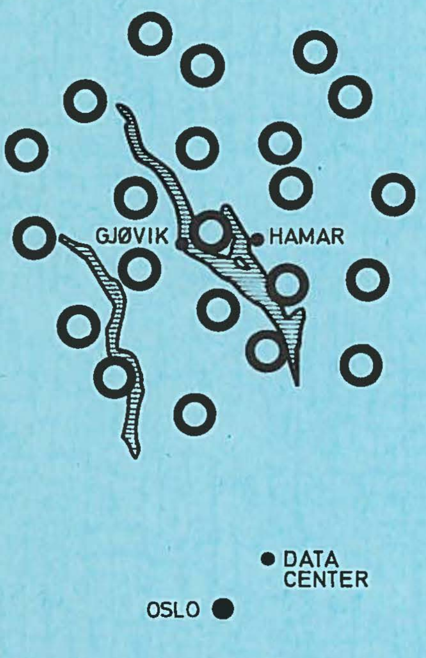

NORWEGIAN SEISMIC ARRAY

NORSAR

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Abstract

To take full advantage of recent developments in seismological theory and sophisticated interpretation methods requires that high quality data is easily available for research purposes. As of today, the large number of seismological observatories in operation, produce a tremendous amount of quantitative data which is hardly accessible for the seismological community. The latter problem prevails even for the large aperture seismic arrays which are characterized by a new seismic observation concept, advanced recording and standardized analysis techniques. In this paper we compare different types of seismic wave recording systems, and discuss relevant data handling problems. It is concluded that array processing techniques could be adapted to ordinary station networks, requiring coordination and cooperation in seismograph operation on a regional basis. In this way data quality and accessibility could be improved, but at the same time reducing the costs involved in running the global seismic network.

1 Introduction

As a prelude to this paper we would like to give a few excerpts from a paper by Keilis-Borok (1964):

> "It turns out that the variety of seismological studies in principle can be fitted into systematic order. But in reality, as we have seen, there is no systematic order as yet: large entropy is introduced by disunity of the work. To restore order is not enough (although important) to understand the logical structure of seismology. This structure must be realized: first, by an introduction of unified and universal recording equipment; secondly, by a formalization of the standard elements of interpretation (which will make it possible to automate them), thirdly, by a presentation of the results of interpretation in a compact unified form. Then the seismologist could be disentangled from routine work."

The logical structure of seismology as visualized by Keilis-Borok in 1964 has to some extent been realized for the large aperture seismic arrays. Typically, the disunity in instrumentation, recording mode, and data interpretation still prevails when we compare the American and British built array systems. However, the seismic data contributions from arrays is modest relative to that from the around 1100 conventional seismograph stations in operation which produce roughly 1 million records annually. The data contribution from the global network has proved a great asset to seismology in the past, but in order to comply with increasing demands for high quality seismic data some modifications must be introduced in the present operational modes of various types of seismograph stations. These problems are the topic of this paper, and we hope that our ideas here could arouse the interest of the seismological community.

2 Seismic Arrays

One of the most useful techniques for improving our capability to observe and subsequently analyze seismic events is to combine a number of seismic sensors distributed on the earth's surface so as to form an array. Looking back on the ten years' history of seismic arrays, it seems logical to group them in the following way:

1. Tripartite stations and "Geneva" arrays
2. Large aperture seismic arrays like NORSAR (Norway)
3. Continental arrays like the Fennoscandinavian seismograph network.

The first two groups are representing different generations in array development, characterized by differences in sensor numbers, geometrical dimensions, recording modes (analog/digital), and extents of data processing. The concept of continental arrays is the result of applying selected parts of array processing techniques to seismic data from conventional stations.

There are several ways in which we may describe an array. Definations which are related to physical properties and dimensions of such systems are interesting enough, but not entirely satisfactory. One of the fundamental characteristics of an array is that it adds a new dimension to seismic wave recording, namely, the parameters required to define points on the surface of the earth. At a seismic array the wave sampling is performed both in space (two-dimensional) and time, and then only Fourier transformation is required to convert the observations into the frequency wavenumber space. The capability of filtering in the latter domain is essential (see Fig. 1); such techniques give better signal-to-noise ratio, effective suppression of signal generated noise, and also estimates of velocities and bearings of propagating waves (e.g. Capon 1969). In addition, signals observed in real space, provide a wave-front solution which is determined or over-determined dependent on the number of sensors and degree of polynomia used.

It should be noted that for continental arrays the wavenumber concept is not meaningful as this parameter is not part of the solution of the wave equation in spherical coordinates. On the other hand, the beam-forming technique is very useful. For comparison, at a conventional station the data is sampled at one point in space; we get one single time series and seldom know t what extent this is representative for the seismograph region or even the local area. In the latter case we may observe absolute values of wave arrival times and amplitudes contrary to an array which measures gradients like wave velocities, relative amplitudes (dlogA), etc.

3 Seismic Wave Recording and Data Handling Problems

It is natural to differentiate between large aperture seismic arrays and ordinary seismograph networks because these systems are not easily comparable and also present us with different types of operational problems. On the other hand, concepts and analyzing techniques built into seismic arrays may be adapted to seismograph networks and thus improve the data output of the latter systems.

3.1 Large Aperture Seismic Arrays

If we consider an array like NORSAR as an independent seismic wave observation system, it represents unified recording equipment, automated data interpretation and result presentatio in a compact unified form (Bungum et al 1971). In order to demonstrate the objectiveness of array data processing, a short description of event detection and m_b magnitude measurements at NORSAR (IBM 1967) will be given. The "eye-ball" logic involved in reading seismograms is impossible to computerize, so the chosen procedure here is the following:

A short term average (STA) is calculated through a rectangular window (length around 2 sec), and a long term average (LTA) is calculated through a recursive exponential filter which gives an estimate of the noice. The two filters then slide through sensor or beam traces in real-time, and when the STA/LTA ratio exceeds a given threshold a specified number of times a detection is declared. NORSAR-observed STA, LTA and STA/LTA values are shown in Fig. 2. This test is performed simultaneou ly on up to 400 beams, and extensive processing is done in order to eliminate false detections and to localize the true detections. All this takes a considerable amount of computer time, and actually ties up one IBM 360/40 computer completely. (In addition extensive off-line processing is done by another computer.)

The computerized m_b magnitude estimation is demonstrated in Fig. 3. The principle in use here is that measured signal power is proportional to kinetic energy of the P-waves as the SP instruments in use at NORSAR are essentially velocity measuring devices. As it is well known, Richter's magnitude definition is implicitly tied to the kinetic energy of the recorded waves through the inclusion of the A/T term. Typically for some of the disorder in seismology is the fact that several magnitude formulas are in use, different equations used for transforming one magnitude scale into another, and different formulas used for relating magnitude to the energy released by earthquakes (Båth 1966).

The seismic arrays represent a significant step toward a more unified approach to preliminary seismic data analysis, although many problems remain to be solved. For example, NORSAR will (when fully operational early 1971) require nearly one digital tape per hour for storing raw data. This means that the tapes must be reused, and a retention period of at most one year is possible within an acceptable economic frame. Only seismic events can be saved permanently, but even this may be optimistic e.g., estimated event recording rate may be around 10 events per hour. Still there are many questions to be answered, like saving all or only a limited number of sensor traces (say, retaining LP and subarray center SP data), proper saving length of the recorded earthquakes, tape administration, i.e., storing events chronologically or as a function of seismic regions, etc. Another problem is array data exchange. NORSAR uses 9 tracks, 1600 bpi tape as standard, but has options for data copying on 9 tracks, 800 bpi tapes. Even so, some institutions may have difficulties in reading NORSAR tapes.

For LASA and NORSAR extensive event processing analysis will be performed daily on a minimum number of events and resulting in a seismic bulletin. The latter includes phase velocity and azimuth measurements, and thereby an estimate of epicenter location. During the event analysis we may have options to extract far more information than that appearing in the bulletin, like power spectra, sensor coherency, group and phase velocities, etc. (Bungum et al 1971).

It is beyond the scope of this paper to go into further details here, but we should like to stress that the combination of digital seismic data - electronic computers for the very first time gives the seismologist an opportunity to be disentangled from routine work. Is our opinion, the response of the seismological community to this challenge has been too modest so far.

3.2 Continental Arrays

In this context a continental array is defined as an aggregate of ordinary seismograph stations which are characterized by analog recording on some sort of paper or photographic film. Obviously, the distribution of individual seismic sensors does not favor the use of these stations as continental arrays in many areas. National considerations usually have counted more when establishing a network than the question of to what extent the stations might fit into a larger pattern. Of course, there are good exceptions - planned or not - like the Fennoscandinavian network. In addition to configuration, the usefulness of the continental array concept is limited due to non-uniform instrumentation and lack of magnetic tape recording. These drawbacks are most obvious for the LP sensor distribution. The problem of coordination and cooperation of seismograph operations in order to rationalize this process, was taken up in 1963 (Båth 1964). Seismologists showed great interest in Båth's ideas, but as time has proved, national boundaries seem to represent scientific boundaries in this respect. Anyway, within the present frame of global seismograph operation, we believe that small modifications in station configuration and seismogram analysis would improve the quality of the extracted wave parameters and at the same time reduce significantly the costs and work involved.

We would like to discuss some aspects of the above problem, and take the Fennoscandinavian seismograph network as a reference system unit. This network has a relatively homogeneous instrumentation (mostly SP Benioff seismometers) and reasonable configuration which is appropriate for P-wave velocity measurements. In fact, the precision in $dT/d\Delta$ using a continental array is very high due to its large geometrical dimensions. For example, the problem of possible existence of lateral velocity variation may definitely be solved when data is available from a number of continental arrays (Husebye & Kanestrøm 1971).

Station sensitivity in terms of number of events recorded per unit time varies greatly over even small regions (Fig. 4). This fact should be fully exploited by restricting the time consuming scanning work involved in seismogram analysis to a few sensitive stations within the network. Based on results obtained here, the reading of remaining stations seismograms could be limited to a few, short time intervals.

Jansson and Husebye (1966) and Whitcomb (1969) have demonstrated that body wave signal similarity is good despite large station separations. If regional centers are established as proposed by Båth (1964), records from all stations would be available and reading and phase identification errors could be greatly reduced, using the "eye-ball correlation" technique. As it is today, bulletin data on secondary arrivals is usually rendered useless due to lack of precision. Other aspects of large aperture array data processing technique like group and phase velocity measurements could be adapted to continental array data. In short, benefits gained by establishing regional centers are that more and better data could be included in the bulletins, and also that seismogram exchange would be facilitated with the total operational costs involved significantly reduced.

4 Discussion

Recent advances in seismology are characterized by sophistications in theory and establishing of powerful techniques for inversion of gross geophysical data. The developments result in requirements for increased precision in observational data. Such data will spur further developments in theory and analysis techniques, and so the circle closes. Today the largest problems seem to be in seismic wave parameter extraction and data exchange as discussed in the previous sections. In our opinion, the seismological community should be much more concerned than hitherto with improving the operation of the instruments in use presently, and also be prepared for further demands for high quality seismic data. In the latter case, the way to go is obviously to install magnetic tape recording equipment and use of small special purpose computers for automating data analysis. Seismic array data processing techniques developed so far could easily be adapted to local types of arrays. This would be a significant step toward more homogeneity in seismic wave recording and routine data analysis.

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Figure Captions

Fig. 1 Representation of signals and noise in frequency-wavenumber space for a fixed azimuth.

Fig. 2 Beam, STA, LTA, and STA/LTA values for earthquake from Tsinghai, China, 27 Feb 1970. Filtered 1.0-3.4 Hz. STA integration time is 1.8 sec, 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 different parameters are set such that we get rapidly out of detection state.

Fig. 3 Procedure for estimating body wave magnitude.

Fig. 4 Histogram of detection frequency for seven Fenno-scandinavian stations. The data cover the period 1-15 March 1970. NORSAR is here represented by only a few sensors in an interim detection system.

Fig. 5 The Fennoscandinavian network of seismological stations. Asterisk indicates stations recently discontinued. Underlined stations have also long period equipment.

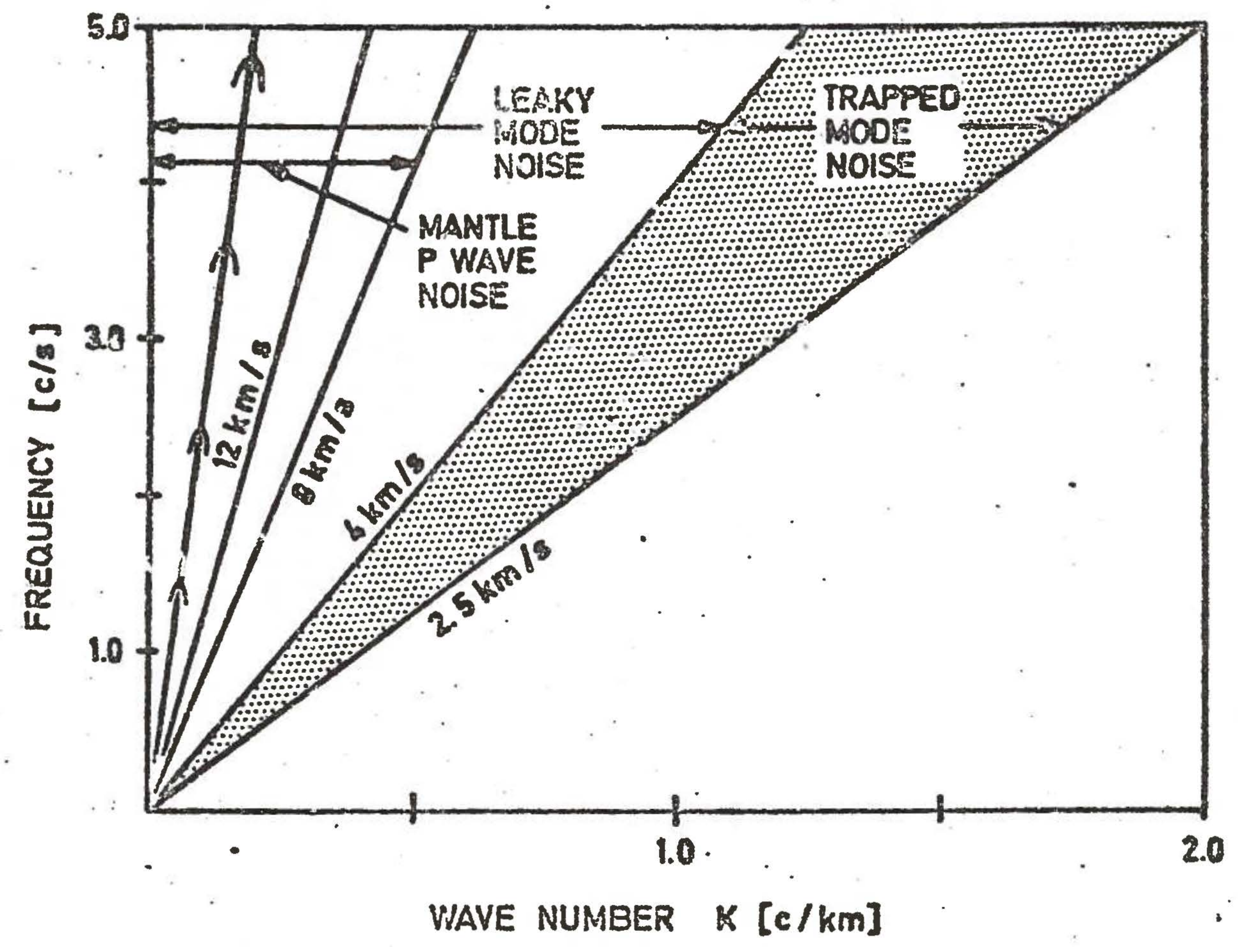
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Fig. 1

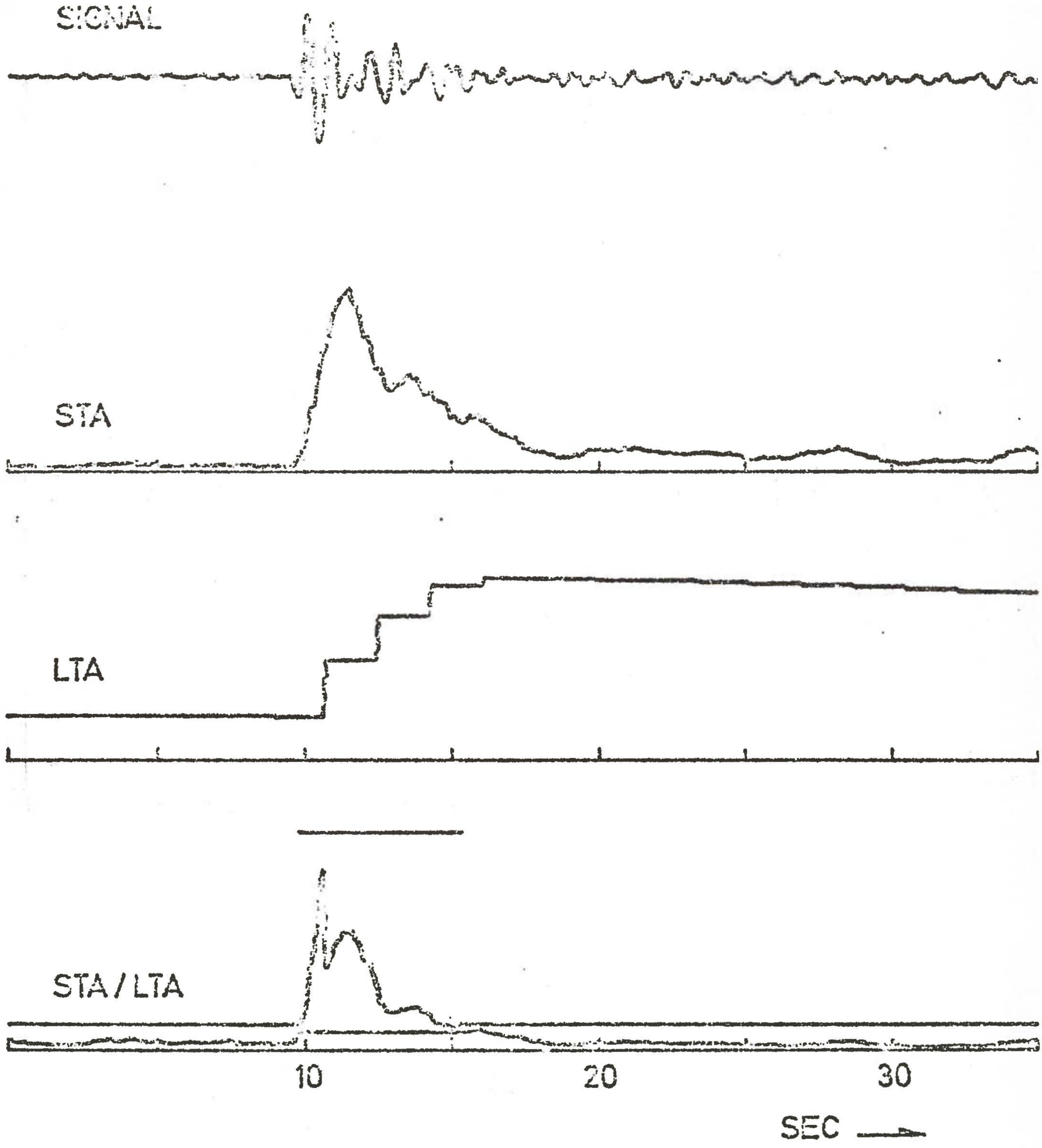

Fig. 2

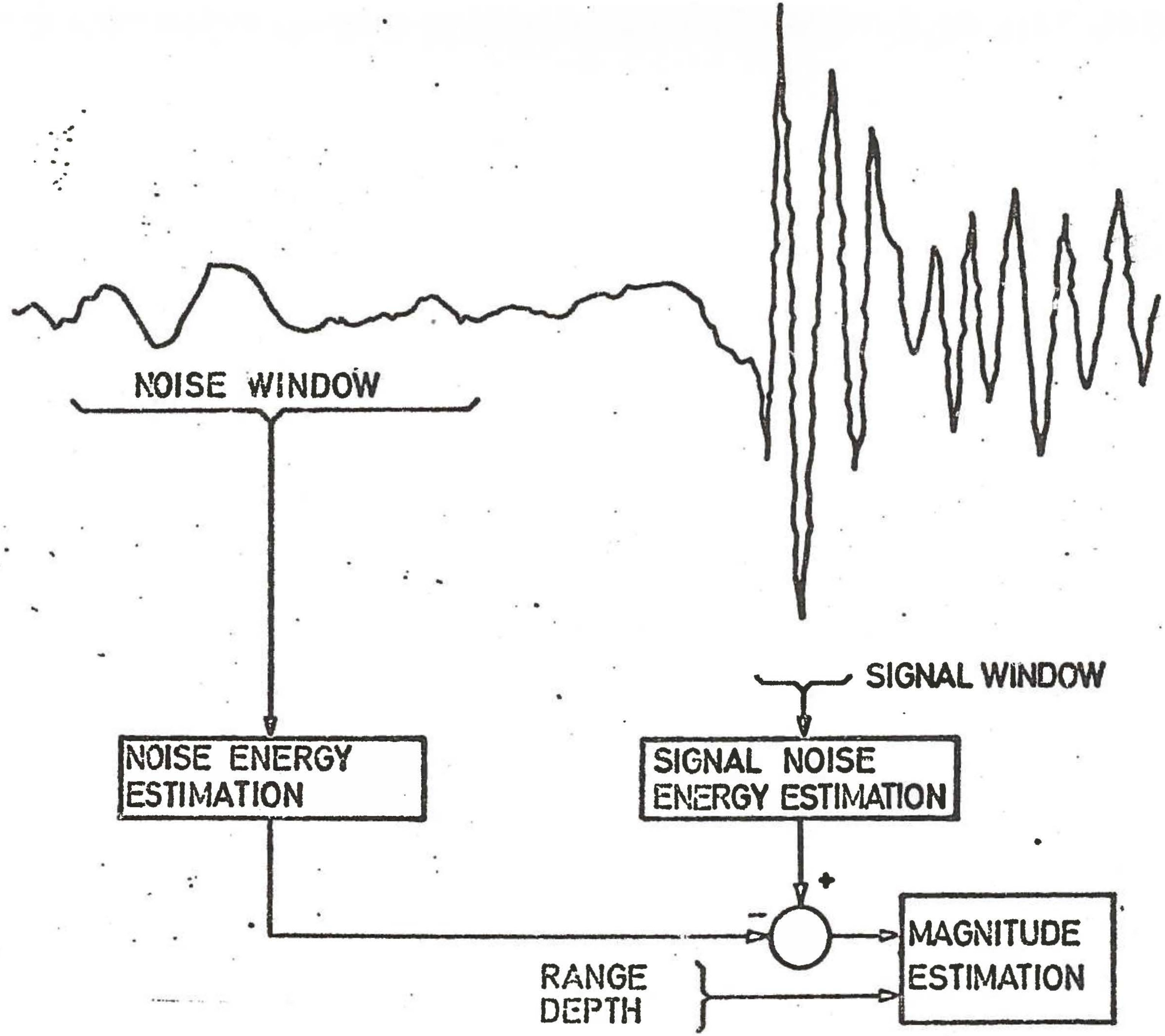
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Fig. 3

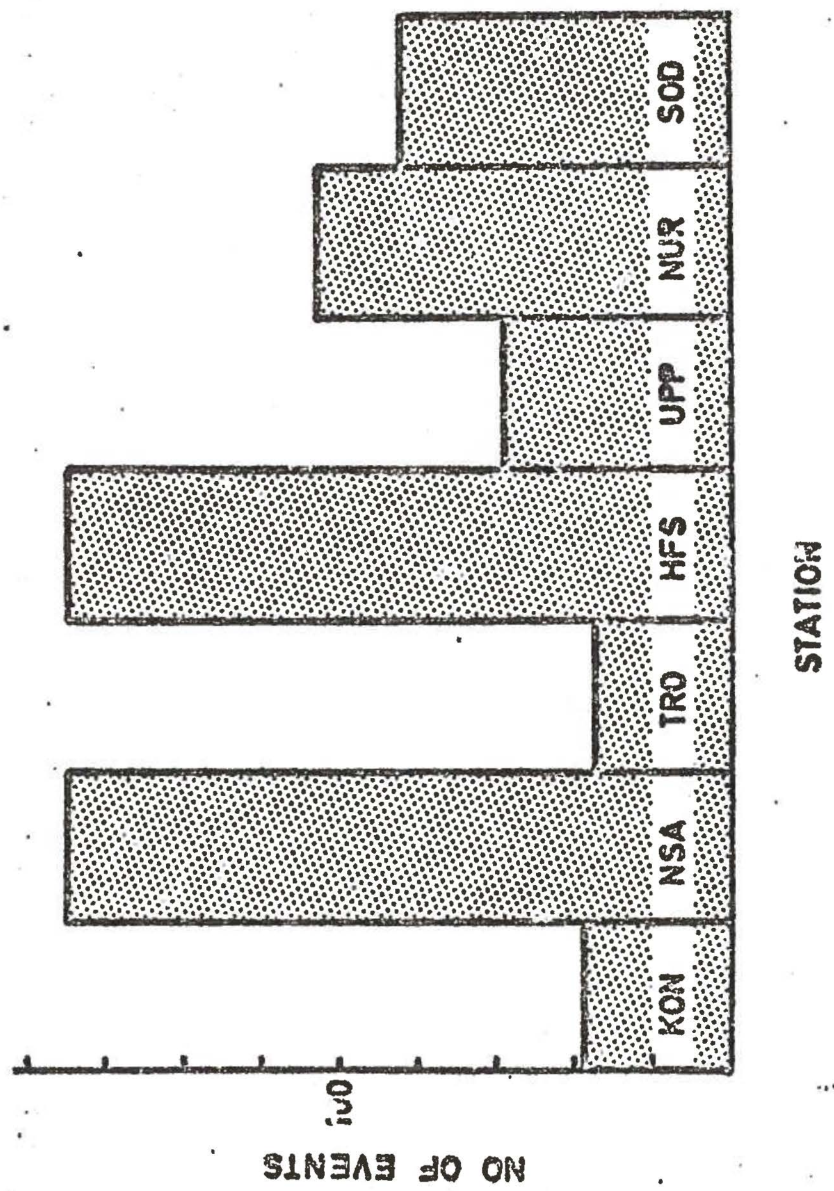

Fig. 4

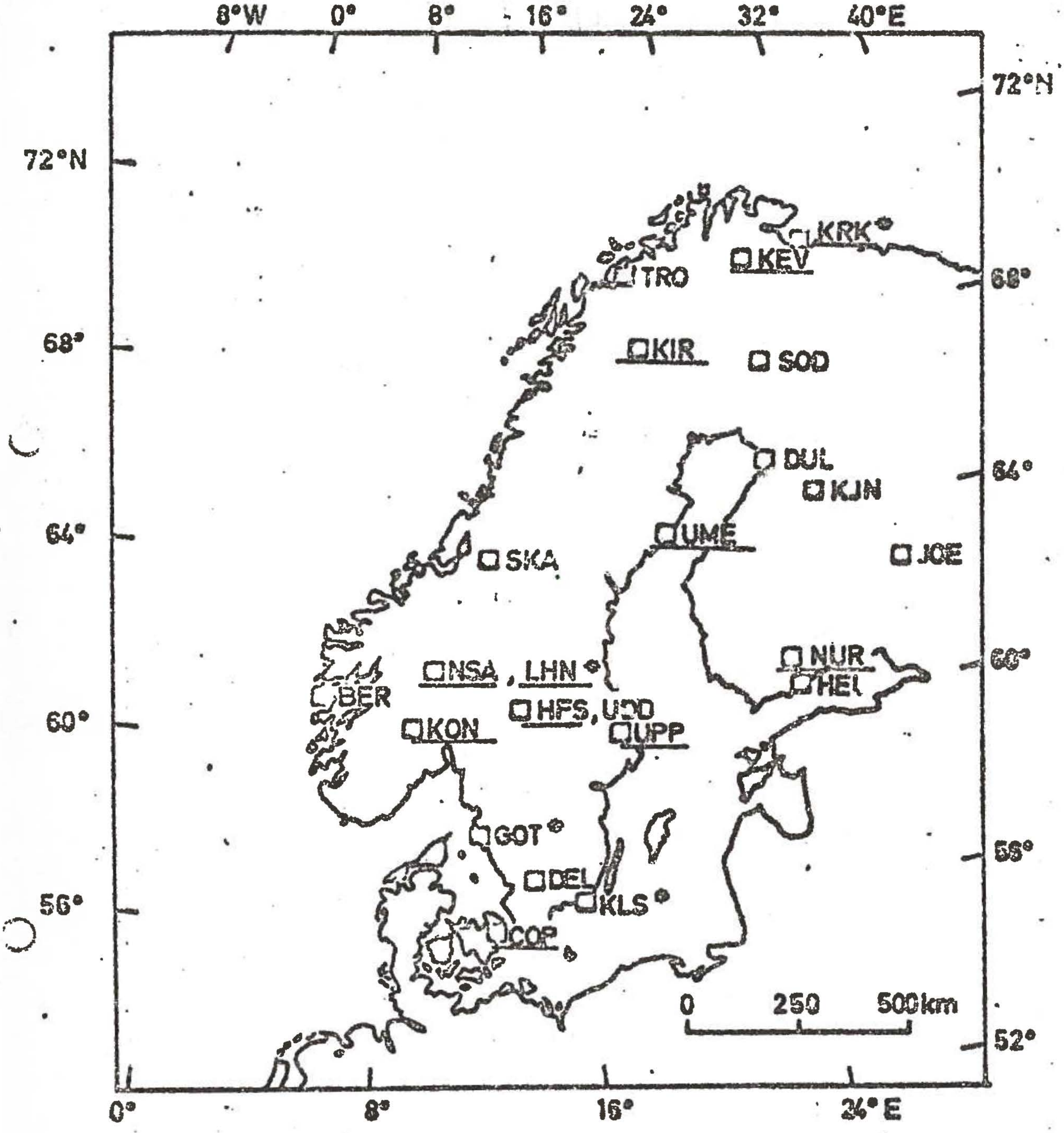
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Fig. 5