Royal Norwegian Council for Scientific and Industrial Research

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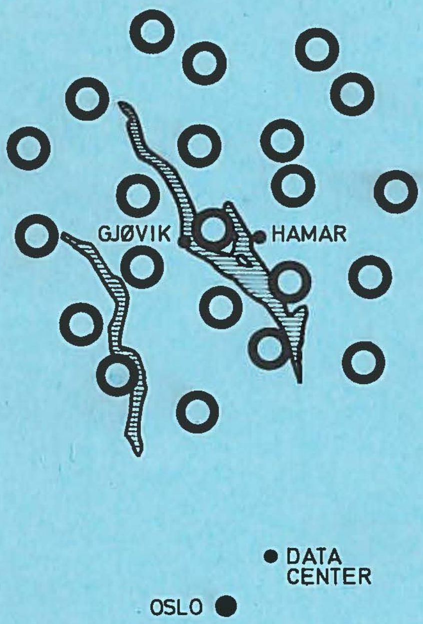

NORWEGIAN SEISMIC ARRAY

NORSAR

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43

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INTRODUCTION

The characteristic feature of a seismic array is real-time processing of data from a large number of sensors organized in a certain pattern on the surface of the earth. The principal aim of array operation is suppression of unwanted noise and at the same time preserving the seismic signals of interest. As is well known, when sensor separation increases, the signal similarity, in general, decreases. The consequence here is that when processing signals from a continental array or the global seismological network, the signal suppression is approximately equal to the noise suppression, resulting in a processing gain close to zero. One possible way to circumvent this problem might be to replace the individual signal trace by its envelope as we intuitively should expect this kind of signals to exhibit a large degree of signal similarity independent of sensor separation, seismometer type, etc. The topic of this paper is to discuss the feasibility of multiarray analysis through simultaneous processing of signal envelopes from the global seismological network.

METHOD AND DATA ANALYSIS

For certain rather simple signal models it is fairly easy to deduce the relationship between the signal and its envelope. Let us assume that the wave profile is split into an infinite number of harmonic waves of the type

$$\exp[2\pi i(kx-vt)] \qquad (1)$$

where k is wave number, v is wave velocity, x is distance and t is time. The amplitudes of these component waves are assumed to have a Gaussian distribution, i.e.,

$$a(k) = A \cdot \exp[(k-k_o)^2 \cdot \sigma] \qquad (2)$$

In this case the envelope Y of the so-called Gaussian wave packet would be for non-dispersive signals (Coulson 1961).

$$Y = A \cdot (\pi/\sigma)^{\frac{1}{2}} \cdot \exp[-\pi^2 (x-vt)^2/\sigma] \qquad (3)$$

If we define the half-width of the envelope as the value $(x-vt)$ that reduces the amplitude to 1/e times its maximum value, it would then be $(\sigma)^{\frac{1}{2}}/\pi$ for the wave packet considered. As the signal envelope shape is a function of only σ or signal spectral bandwidth we would expect high similarities between short period P-wave envelopes even if the signal waveforms are uncorrelated.

The straightforward way of checking P-wave envelope similarity is to perform correlation and coherency analysis of digitized seismic signals recorded by WWSSN stations around the world. This has been done for two earthquakes, Chile 12/20/66 (see Fig 1) and Solomon Islands 08/20/66, and the Greeley nuclear explosion in Nevada 12/20/66. It should be

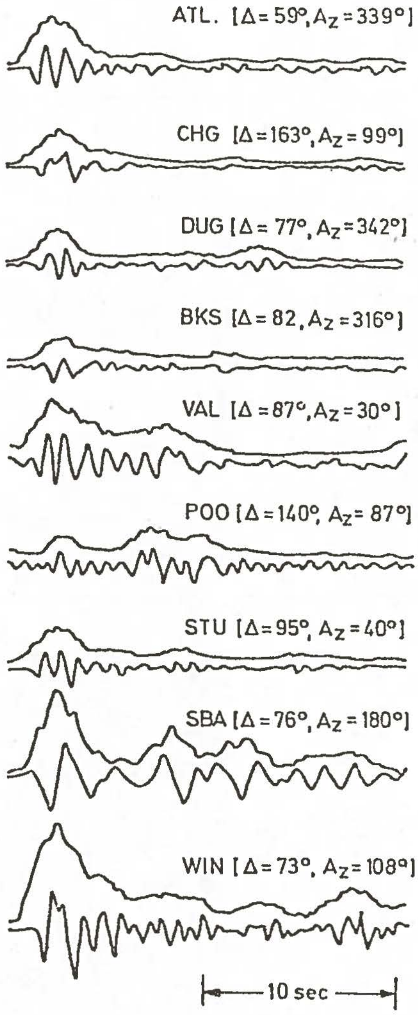

Fig 1. P-signal and envelope traces for an earthquake in Chile 12/20/66 and recorded by globally distributed WWSSN stations. Distance and epicenter azimuth are given in the figure.

noted that in this analysis the envelopes have been defined as the average of absolute P-signal amplitudes in a window of 1.5 sec length and using a sampling rate of 0.1 sec. The average cross-correlation values for all paired envelope com-

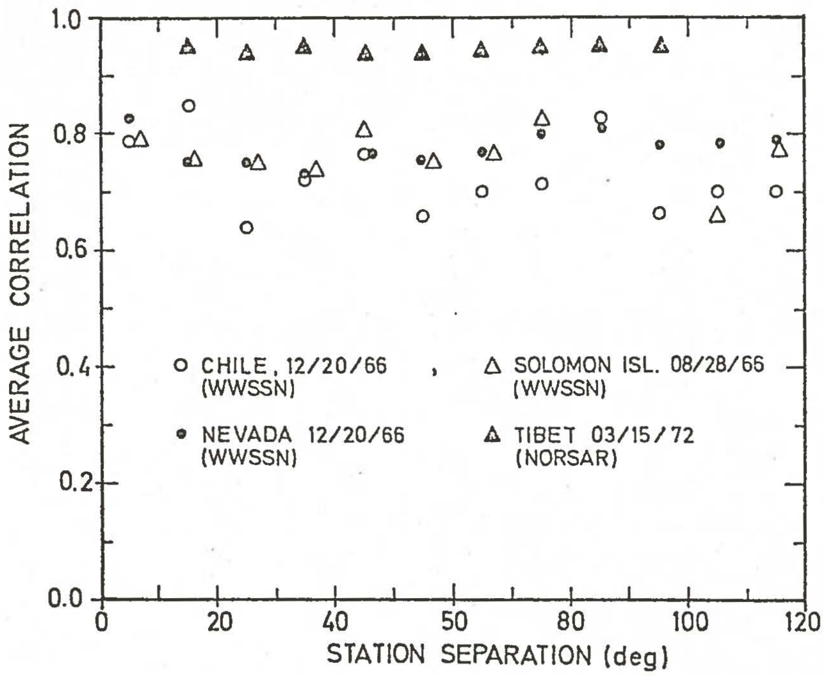

Fig 2. Average of cross-correlation values for all paired station combinations as a function of station separation. When $\Delta \geq 120^{o}$ the distance separation is set equal to 120^{o}. For the NORSAR recorded event, the station separations are in km. Time window length was 12 sec.

binations for the mentioned events are presented in Fig 2 as a function of station separation. A brief summary of the results of the above analysis is as follows: The average envelope correlation coefficient for all station combinations is approximately 0.75. The noise and signal envelope spectra contain relatively much low frequency energy and have roughly identical shapes. This makes it difficult to obtain signal-to-noise ratio (SNR) improvements by bandpass filtering. However, substantial SNR gains are possible by prefiltering the original P-wave traces as expected from eq (2) and this has also been verified experimentally (Felix et al, 1972).

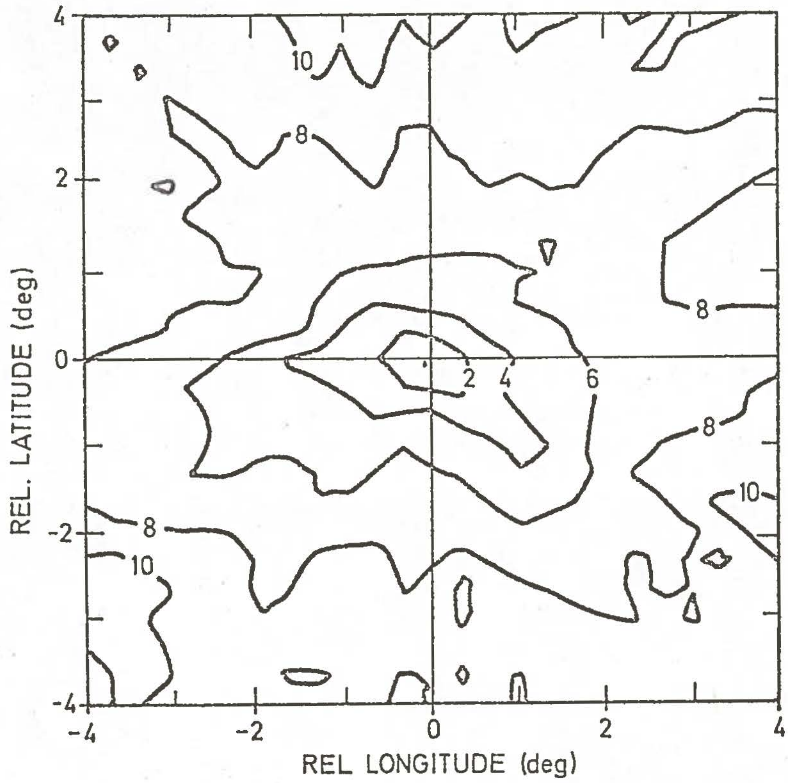

Fig 3. Response pattern for the Greeley nuclear explosion in Nevada 12/20/66 based on envelope traces for 19 WWSSN stations.

So far we have demonstrated that the signal envelopes exhibit sufficient signal similarity so that an ensemble of such stations might be considered a continental or global array. The main advantage of such a system would be to improve the global seismic event detectability based on array detection processing on envelope beams. An example of the response pattern for a global network comprising 19 WWSSN stations for the Greeley nuclear explosion is shown in Fig 3.

DISCUSSION

The main question when considering the potential of the global network is the possible gain in seismic event detectability and whether this kind of processing is technically feasible, and we will try to answer both of these questions. The starting point is beamforming processing on envelope traces and this operation does not give any noise suppression, and thus does not enhance the signal-to-noise ratio (SNR). However, the envelope beam exhibits a noise variance which is reduced by a factor of N (= no. of sensors) from the single sensor level, so that the event detectability is improved by a factor of $\sqrt{N}$ (Ringdal et al 1972).

Actually, it is possible to have additional pseudo gains in detectability for envelope processing, i.e., to provide P-wave noise suppression by bandpass filtering and to restrict the global network to exceptionally good stations. From theoretical considerations we should expect the signal amplitude distribution across a number of stations to be lognormal, and this hypothesis has been supported by relevant data analysis (Ringdal et al 1972). Using this model and estimating the parameters involved, it is possible to theoretically predict the cost/performance trade-off regarding the number of stations required for optimum event detectability.

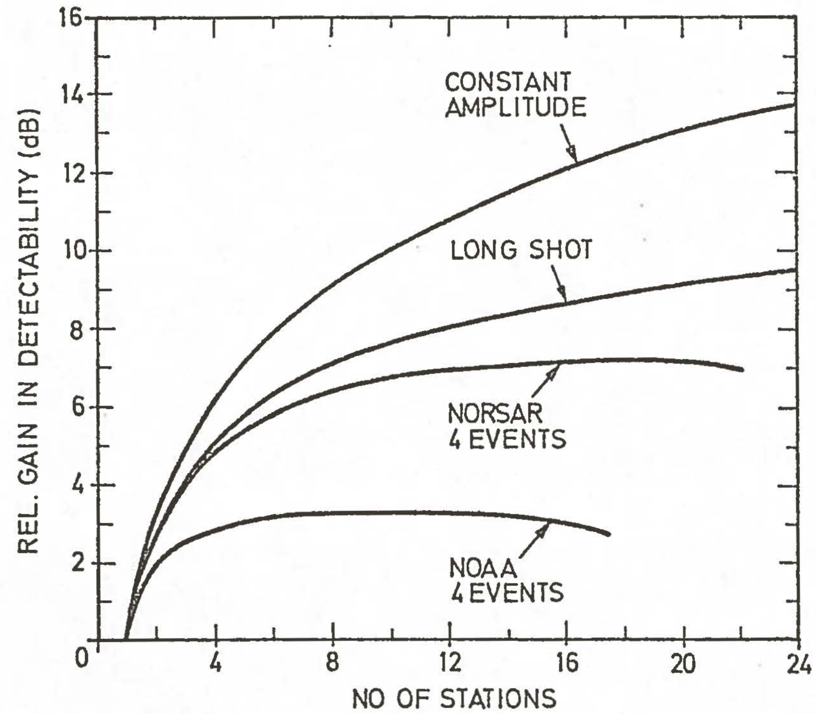

Fig 4. Gain in event detectability relative to the station having the largest amplitude. ~~Eq (4) was used, and the noise level was taken as a constan~~t. The NORSAR and NOAA events used in analysis were picked randomly from their respective bulletins.

The importance of the statistical amplitude variations of P-waves in the teleseismic range 30-90° using data from NOAA, NORSAR and Long Shot (Lambert et al 1969) is demonstrated in Fig 4.

It is very interesting to note that the number of stations actually needed for optimum event detectability in a given seismic region is remarkably few, as around 8-16 stations are required for ensuring maximum envelope processing gain for all practical purposes. However, for global seismicity coverage many more stations are required due to intrinsic amplitude variations. A typical example here is the NORSAR array where the signal amplitudes for one subarray may be consistently large for one region and poor for another region as shown in Fig 5.

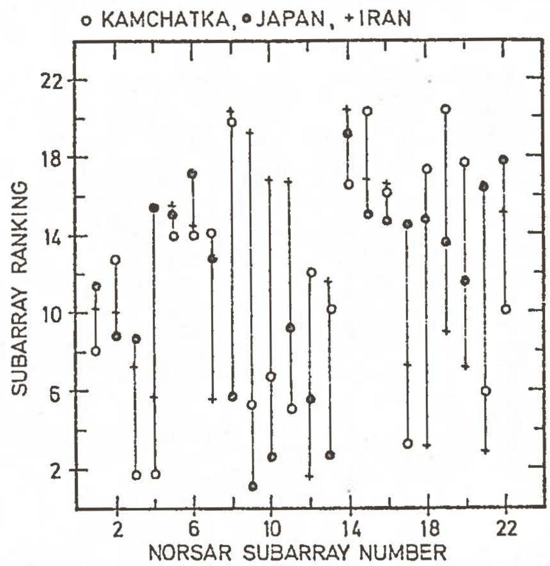

Fig 5. NORSAR subarray amplitude ranking for earthquakes occurring in the Kamchatka, Japan and Iran regions. The number of events used in analysis was 21, 16 and 10 respectively. In each case the Kendall rank correlation test (Siegel 1956) gave highly significant results.

Finally, we should like to forward some comments on the technical implications of real-time multiarray processing. First of all, restricting the network processing to envelope traces means that a 2 or 1 Hz sampling rate would be sufficient. Data transmission to a common processing center could thus easily be achieved as a standard telephone line can handle at least 75 envelope traces. At present, the large aperture arrays ALPA (Alaska), LASA (Montana) and NORSAR (Norway) are exchanging seismic data in real time via the telephone network and a communications satellite. It would be feasible within a global seismic network as outlined above to include the envelopes of the 300 array beams deployed at LASA and NORSAR as single, highly sensitive channels. These beams could then be combined with traces from single stations or smaller arrays in the subsequent joint envelope beamforming. Due to the small sampling rate and relatively long periodic nature of the signal envelopes, a small computer could handle the required detection processing, including deployment of a few thousand beams required for adequate coverage of all seismic regions.

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