ROYAL NORWEGIAN COUNCIL FOR SCIENTIFIC AND INDUSTRIAL RESEARCH

PROCEEDINGS FROM THE SEMINAR ON

SEISMOLOGY AND SEISMIC ARRAYS

OSLO, 22–25 NOVEMBER 1971

Editors: E S Husebye and H Bungum

Arranged in connection with the opening of The Norwegian Seismic Array (NORSAR) 1972

DISPERSIVE FILTERING FOR SNR GAIN

EIVIND RYGG

Seismological Observatory, University of Bergen, Norway

ABSTRACT

A method is suggested to compensate for the dispersion of surface waves before delay and sum (DS) processing. Although we tested data for very distant sensors we found that a compensating filter generated for one event, gave satisfactory corrections when applied to the recordings of another event.

INTRODUCTION

The delay and sum or beamforming procedure is a fast and, dealing with properly spaced arrays, very efficient way of increasing the signal to noise ratio (SNR). This applies especially to the short period P-wave signals (Capon et al, 1968) but also considerable SNR gain in long period beamforming has been demonstrated (Capon et al, 1969).

Quite often, however, seismologists have experienced considerable lack of signal coherence and consequently loss of beamforming gain even across moderately sized arrays. While the lack of coherence for short period teleseismic signals, indicates geological differences beneath the recording sites, the dispersion and attenuation of the surface waves are due to the structure between the instruments. Therefore, the effectiveness of applying beamforming to an array consisting of long period instruments depends on the horizontal extension of the array, as well as the geological substructure within it. In this paper we develop the dispersive filter function of the earth between two well separated stations and apply this function to correct for the dispersion between the stations.

THE LONG PERIOD BEAMFORMING PROBLEM

The normal procedure for beamforming long period data is to steer the array using the velocity of one signal spectral component. Mainly because of the magnitude calculations, one is in general interested in the 20 sec Rayleigh wave and the long period beam is frequently formed using the 'best velocity' for this period across the array. The best velocity can be estimated by power density analysis in frequency - wavenumber space.

Also, at the existing large arrays the long period instrument response curves peak around 20 sec. Consequently, very often groups of waves around this period will be the most dominating feature on the recordings. Sometimes this is the only surface wave that can be observed, and in these cases the beamforming procedure described above is satisfactory. However, if the instruments are broadband, the normal long period recording will be a train of waves. When the sensor spacing is large (of the order of 100 km or more) one has to correct for signal dispersion across the array in order to ensure that the waves are in phase throughout the entire wavetrain.

Fig 1 shows a typical example of the difference between the broadband Kongsberg and the NORSAR recording of a Rayleigh wavetrain. The traces in Fig 1a represent the LPZ NORSAR output. The signal comes from an Afghanistan - USSR border region event of 1 Oct 1971 - origin time 16.27.35, m_b = 4.6 (from the NORSAR preliminary seismic event summary). The distance perpendicular to the wavefront between the instruments at 05C and 01C is of the order of 65 km. The degree of dispersion between these two subarrays is indicated by the convergence of the thick lines. We notice that while the wavetrain that can be positively identified by eye at NORSAR is about 3 min, the Kongsberg broadband wavetrain extends to about 10 min.

COMPENSATING FILTER

If we consider the surface waves from an event with its epicenter located on or near the great circle path through two identical seismograph stations, the medium between the sites will be responsible for the different outputs. The effect of the medium can be expressed

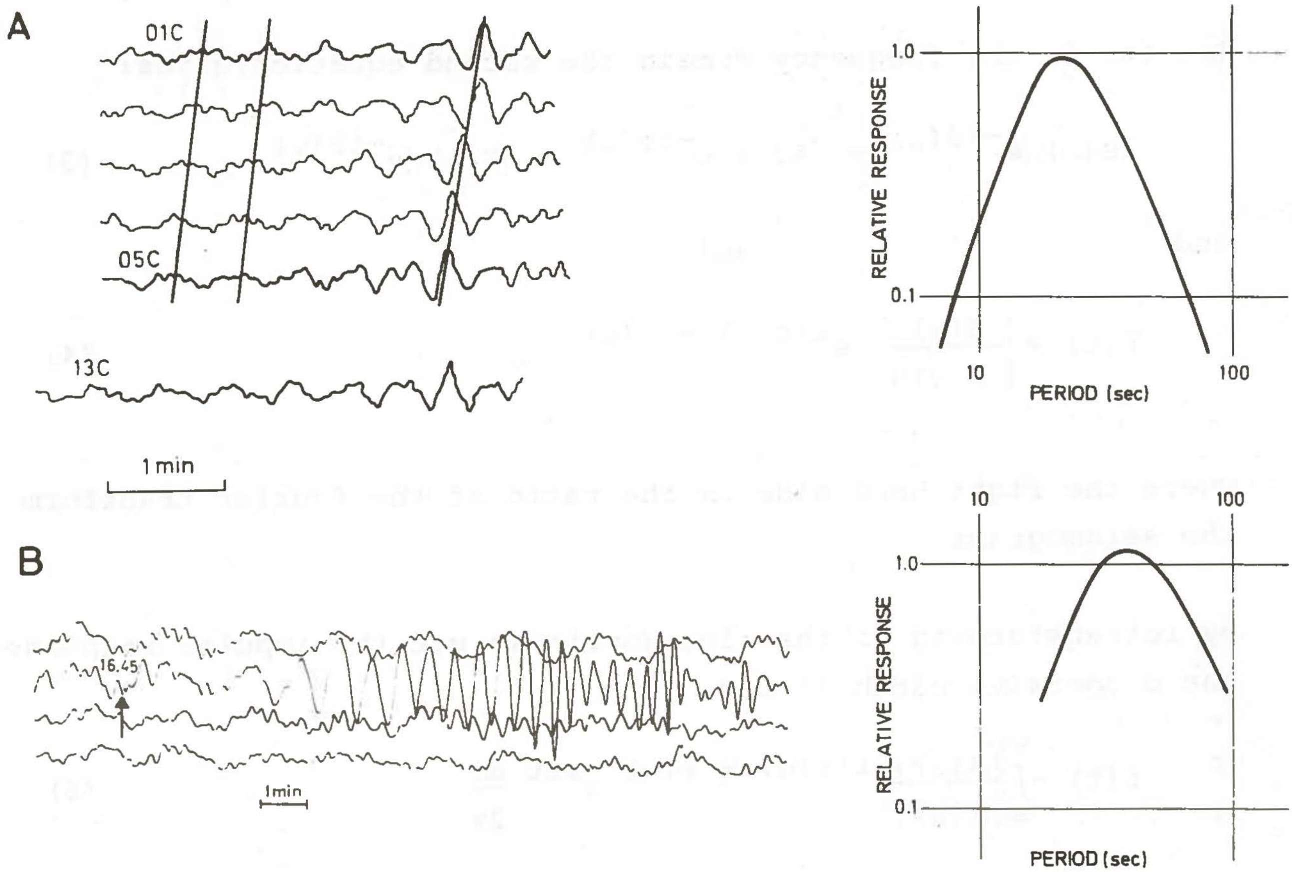

Fig 1 a. NORSAR LPZ recordings of an Afghanistan - USSR border region event of 1 Oct 1971. The instrument response to the right.

b. The Kongsberg broadband high gain recording of the same event as in Fig 1a. The broadband instrument response to the right.

as a dispersive, time domain convolution filter. In general case for a signal travelling the great circle path between the two stations, the different outputs are due to the convolution of the signal received at the first station with the impulse response of this dispersive filter.

Let i(t) be the instrumental impulse response; s(t) the signal entering the station located nearest the source, and f(t) the impulse response of the dispersive 'earth filter'. Assuming the instruments to be identical, the recordings a(t) and b(t) at the two stations will be respectively:

$$a(t) = s(t) * i(t) \quad (1)$$

$$b(t) = s(t) * i(t) * f(t) = a(t) * f(t) \quad (2)$$

Written in the frequency domain the second equation gives:

$$|B(\omega)| e^{-i\psi(\omega)} = |A(\omega)| e^{-i\phi(\omega)} \cdot |F(\omega)| e^{-i\theta(\omega)} \quad (3)$$

and and

$$F(\omega) = \frac{|B(\omega)|}{|A(\omega)|} e^{i\{\phi(\omega) - \psi(\omega)\}} \quad (4)$$

where the right hand side is the ratio of the fourier transform of the seismograms.

By retransforming to the time domain we get the impulse response of the dispersive earth filter:

$$f(t) = \int_{\omega_1}^{\omega_2} \frac{|B(\omega)|}{|A(\omega)|} e^{i\{\phi(\omega) - \psi(\omega)} e^{i\omega t} \frac{d\omega}{2\pi} \quad (5)$$

The integration limits ω_1 and ω_2 define the range of the spectral calculations, and the time series f(t) formed this way will be band-passed within these limits.

When convolved with the signal recorded at the first station this time series compensates for the dispersion between the two stations. Conversely the inverse of the filter can be used to deconvolve the output of the most distant sensor before beamforming the signals.

DATA AND RESULTS

We will in the following give examples of applications of the theory outlined, using the very large aperture two-sensor array Kongsberg (KON) and Kirkenes (KRK) outlined in Fig 2. The events chosen for this study had their epicenters in the Sino-Soviet region and close to the great circle path through the two stations. The raw traces were digitized at a rate of 0.5 to 2 sec and then equispaced with 1 sec intervals by linear interpolation. The impulse response of the

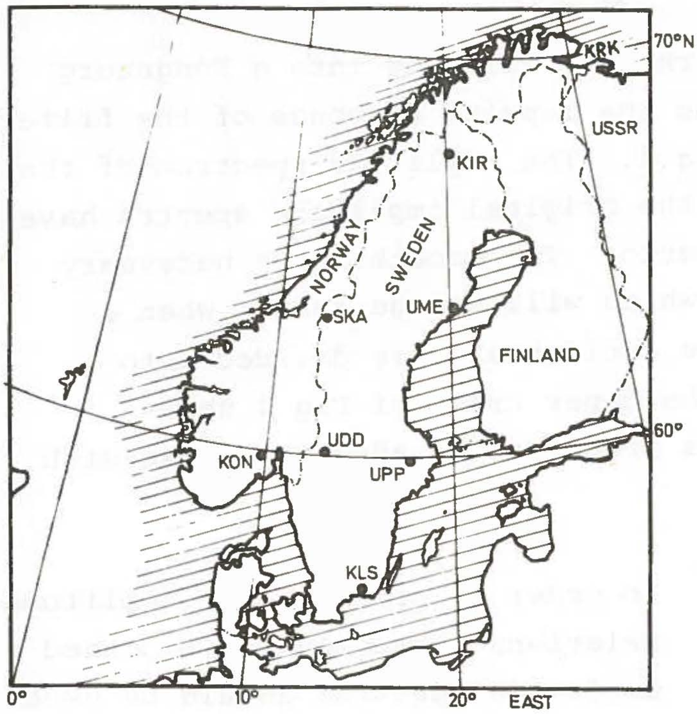

Fig 2. Location map of Kongsberg (KON) and Kirkenes (KRK) seismograph stations.

filter expressing the dispersive character of the earth has been calculated at a length of 1000 sec. The signal energy spectra shown in the figures have been smoothed by using a five sample window in the frequency domain, with double weight on the center sample.

Fig 3 shows the KRK and KON LPZ-recordings of a Novaya Zemlya underground nuclear explosion of 7 Nov 1968. The energy spectra of the traces are given in the upper part of the figure and we notice that the high frequency content of the Kirkenes recordings has been strongly attenuated when the signal reaches Kongsberg.

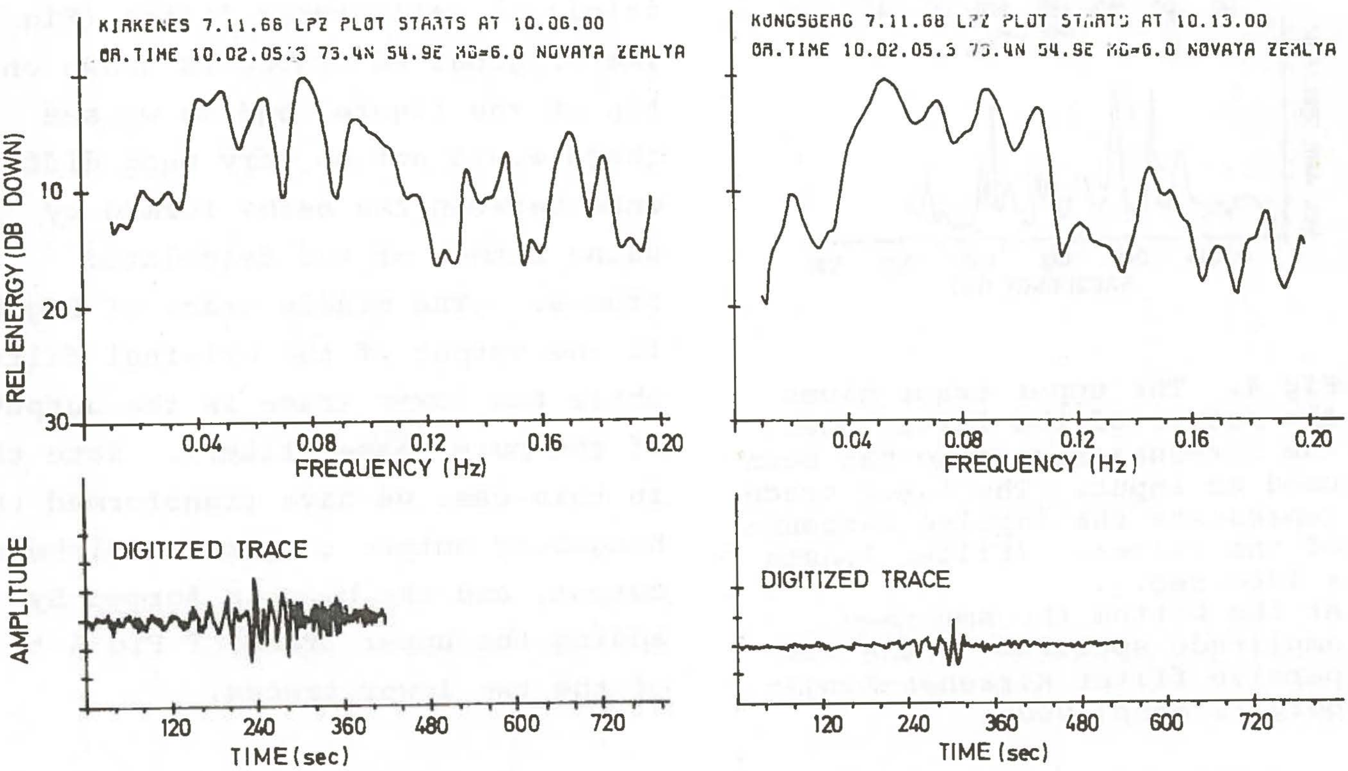

Fig 3. Kirkenes and Kongsberg LPZ-recordings and energy spectra of a Novaya Zemlya underground explosion of 7 Nov 1968.

The filter that transforms the Kirkenes recording into a Kongsberg recording has been constructed and the impulse response of the filter is shown in the lower trace of Fig 4. The amplitude spectrum of the filter is rather rough, although the original amplitude spectra have been smoothed before taking the ratio. The smoothing is necessary to avoid unwanted spectral peaks which will be the result when a 'cut' in the spectrum of one trace accidentally is divided into a 'top' of the other spectrum. The upper trace of Fig 4 shows the output of the filter, and this trace can be added in phase with the Kongsberg trace of Fig 3.

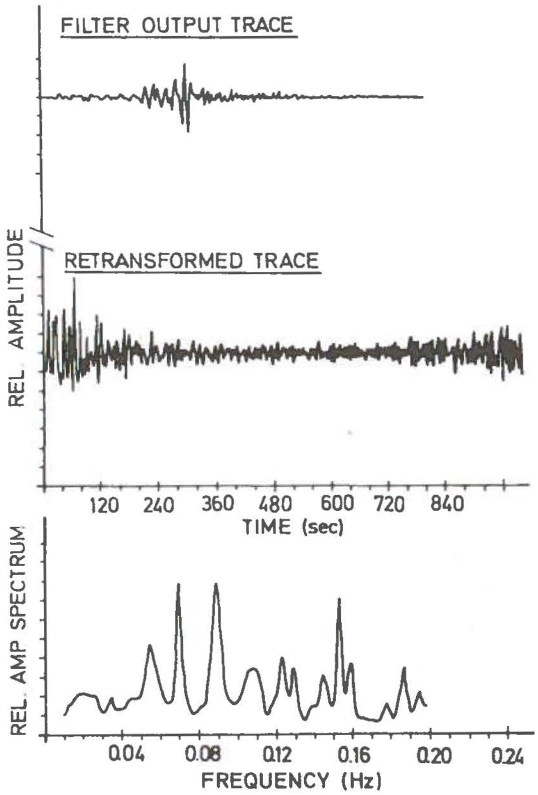

Fig 4. The upper trace gives the output of the filter when the Kirkenes recording has been used as input. The lower trace represents the impulse response of the filter. (Filter length = 1000 sec.).
At the bottom the smoothed amplitude spectrum of the dispersive filter Kirkenes-Kongsberg is displayed.

In order to preserve the amplitude relations correctly the smoothed amplitude spectrum should be used to construct the filter as it has been done here. However, the results also proved to be acceptable by disregarding the attenuation of some frequencies and use a pure phase filter (flat amplitude response). This has been done, and the result has been compared to the output of the original, unflattened filter (Fig 5). The original recording is shown on top of the figure, and as we see there would not be very much difference between the beams formed by using either of the calculated traces. (The middle trace of Fig 5 is the output of the original filter, while the lower trace is the output of the pure phase filter). Note that in this case we have transformed the Kongsberg output to get the Kirkenes output, and the beam is formed by adding the upper trace of Fig 5 to one of the two lower traces.

As demonstrated we can get an acceptable result by using a flat transfer function between Kirkenes and Kongsberg, and of course the result

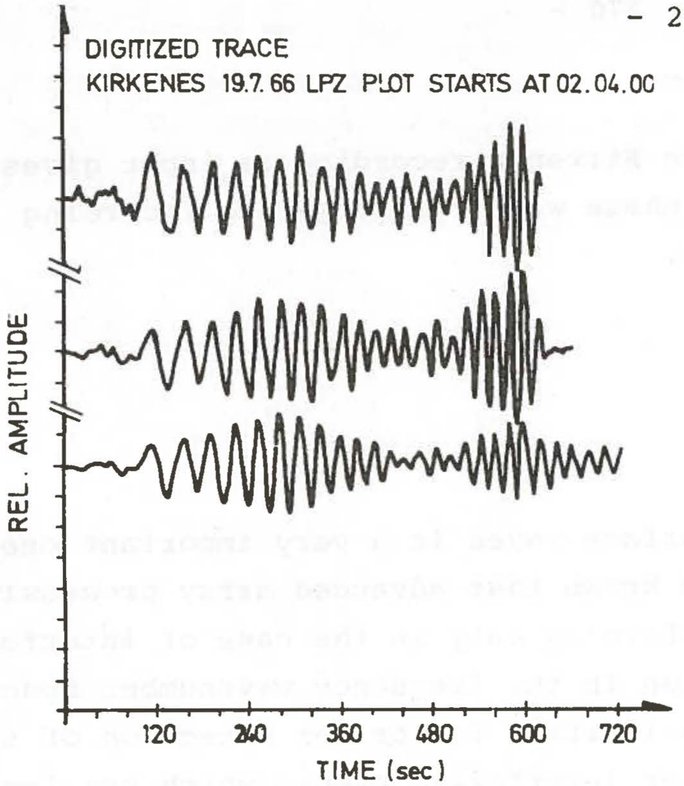

Fig 5.

Upper Trace: Kirkenes LPZ-recording of the Kamchatka earthquake of 19 July 1966.

Middle Trace: The output of a filter generated to transform the Kongsberg recording to the Kirkenes recording.

Lower Trace: The output of the same filter with unchanged phase but with flat amplitude characteristics.

would be less in error the less the distance between the sensors. Inside an array (not too large) the dispersive properties can be expected to be very much the same in all directions. The filters established would thus be a function of distances between sensors only, and the only parameter of importance is the sensor separation in the azimuth direction. In our case the distance between the sensors is very large and the attenuation and dispersive effect of the medium on signals travelling the opposite direction has not been examined.

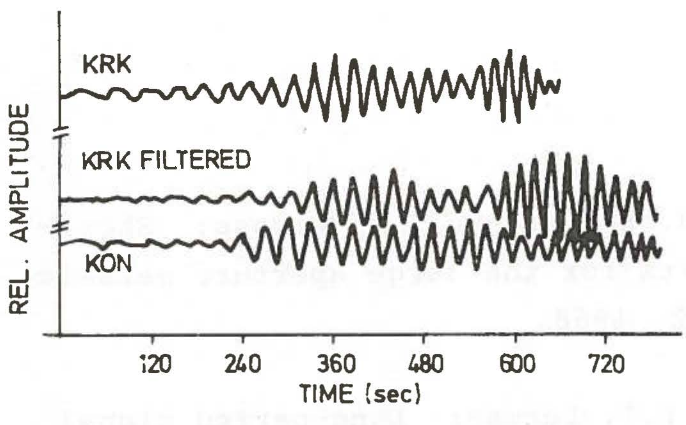

Fig 6.

The upper and lower traces are the Kirkenes and Kongsberg LPZ-recordings of a Kuriles Is. earthquake of 4 June 1966. Location is 46.5N, 152.7E and magnitude $m_b = 5.6$. The middle trace shows the output when the KRK recording has been convolved with a dispersive filter generated for another event. (19 July 1966, 56.2N, 164.9E, $m_b = 5.4$.)

Finally we present an example where the filter that compensates for the dispersion between Kirkenes and Kongsberg has been constructed for one event and applied to another at approximately the same azimuth (Fig 6). The epicenters of the events differ by about 10^{o} in azimuth and they both fall slightly outside the great circle path through Kongsberg and Kirkenes. Therefore we do not really expect the result to be very precise, but as we see from the lower part of Fig 6, the compensating filter with the Kirkenes recording as input gives an output that can be added in phase with the Kongsberg recording almost throughout the wavetrain.

CONCLUSIONS

The problem of enhancing the surface waves is a very important one for discrimination purposes. It is known that advanced array processing shows clear superiority to beamforming only in the case of interfering events with concentrated location in the frequency wavenumber space (Capon et al, 1969). Since the limiting factor for detection of surface waves is very often noise or interfering events which are less concentrated in f.k. space, beamforming is a standard procedure in processing of long period data. If delay and sum processing is used and the aperture is large,some corrections for the dispersion across an array will be necessary.

In this paper correction filters have been developed for the path between the WWSSS stations Kongsberg and Kirkenes. Although we tested data for very distant sensors we found that a filter generated for one event gave satisfactory correction when applied to the recordings of another event. A pure phase filter between the same sites was found to give satisfactory results.

REFERENCES

1. J. Capon, R.J. Greenfield, R.J. Kolker and R.T. Lacoss: Short-period signal processing results for the large aperture seismic array, Geophysics, 33, 452-472, 1968.

2. J. Capon, R.J. Greenfield and R.T. Lacoss: Long-period signal processing results for the large aperture seismic array, Geophysics, 34, 305-329, 1969.