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High-resolution frequency-wavenumber analysis of seismic array data

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The records of arrays are used to measure wavefields and extract information about the sources and the medium through which the wavefield propagates. In seismology, array analysis have been applied in researches such as analysis of seismic coda, estimation of seismic scatterer distribution, measurements of surface wave dispersion, measurements of seismic wavefields associated with volcanic activity, estimation of earthquake rupture propagation and so on. In this study, we present a straightforward and super-resolution array processing technique whose resolution is higher than traditional approaches. In particular, we investigate the applicability of the present method to estimations of high-frequency rupture processes.

The techniques of the array analysis may be divided into two categories, depending on whether they operate in the frequency or in the time domain. In particular, frequency domain approaches have capabilities of resolving multiple signals arriving simultaneously at an array due to multipathing or to multiple sources. One of the simplest frequency-wavenumber methods is the beam forming or conventional (CV) method. The estimated power spectrum can be shown to be a convolution of the array response with the true power spectrum. Here the array response is determined completely by the number of sensors and spatial distribution. Since the array response has a broad beam width for the incident signal's wavenumber and side lobes, the power spectrum estimated by the CV method is blurred by the array response. The minimum variance distortionless (HR) method (Capon 1969) has been shown to produce significantly higher resolutions for the identified wave than the CV method. However, the resolving power of the HR method is similar to that of the CV method when multiple waves are present. For the direction finding of the multiple signals, Schmidt (1986) proposed a signal subspace approach named as multiple signal characterization (MUSIC) method. Key to the performance is the division of the information in the spatial cross-covariance matrix of the Fourier coefficients into two vector subspaces, one a signal subspace and the other a noise subspace. This approach allows for high-resolution estimates of power spectrum since it does not convolve the true spectrum with the array response. A disadvantage is that the method requires as inputs the number of signals which is unknown parameter in many cases.

In this study, we present a straightforward and high-resolution array processing technique by deconvolving the observed power spectrum with the array response in the wavenumber domain. The solution to this problem is determined using non-negative least squares because the power has a positive quantity. When we are concerned with non-dispersive waves such as body waves, it is possible to increase the resolution by stacking the frequency-slowness power spectra corresponding to a set of frequencies (Spudich and Oppenheimer 1986).

To illustrate the utility of the present method in resolving two closely separated signals, numerical tests are performed with synthetic waves composed of two Ricker wavelets adding white noises. The CV and HR method failed to resolve the two sources, while our method and MUCIC method succeeded. It should be noted that the resolution of our method is superior to that of the MUSIC method. We then investigate the applicability of the present array processing method to estimations of high-frequency rupture processes following Spudich and Oppenheimer (1986) by numerical simulations and analyzing array data of 1999 Chi-Chi earthquake.

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