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USE OF SMALL PROGRESSIVELY EXPANDING SEISMIC ARRAYS FOR COMPREHENSIVE MONITORING OF MICROSEISMS

S. K. ARORA[1] & S. PASARI[2]

[1]Ex-Head, Seismology Division, Bhabha Atomic Research Centre, Mumbai, India

[2]Birla Institute of Technology and Science Pilani, Pilani Campus, Rajasthan, India

ABSTRACT

Microseismic ground motion produced, as Rayleigh-type surface waves in a wide frequency range, by either natural or artificial (man-made cultural) sources can be gainfully employed, for determining the sedimentary structure of layered crust from phase velocity dispersion data acquired, at seismometric arrays. The properties of a large aperture array to resolve long wavelengths, and with station density adequate to suppress wave number aliasing, can be synthesized using smaller arrays in expanding mode. Using synthetic data, it is shown that a 3, 4 or 5-station linear-cross array of orthogonal arms can be progressively expanded successfully, employing suitable procedures to minimize number of station relocations and maintaining the basic array geometry. Assuming plane wave propagation from single as well as multiple sources in different azimuths, we have demonstrated that a 5-station expanding array is comparatively more efficient, in fact just optimum in terms of response, in resolving phase velocities and wave numbers of microseisms, with least bias.

KEYWORDS: Expanding Seismic Arrays, Microseisms, Phase Velocity, Response, Wave Number

INTRODUCTION

Microseisms are ambient ground motions with varying particle displacement and phase velocity as measured on the Earth's surface. These ground motions cover a wide range of frequency, generally from 0.01 Hz to 50 Hz, and often recognized as microseismic noise, which is distinctly different in character from the seismic signals produced by earthquakes. The microseismic noise is sustained by wave motion, principally as Rayleigh wave, whose propagation characteristics carry important information on the elastic interior of the Earth to upper crustal depths. It is well related to the sedimentary structure in the uppermost crustal layer, which is of profound interest to exploration geophysicists in many ways (Asten and Henstridge 1984).

The ground motion, produced by microseisms is broadly classified into three categories, depending mainly on their sources that characterize the microseisms. The first category comprises of artificially generated non-stationary type motions, of fairly high frequency (5-50 Hz) from local (cultural) sources such as animal movements, vehicles running, wind gusts, rain showers, air and rail traffic, industrial activity, and the like. In such a case, seismic array response to a plane wave is not applicable. The second category consists of non-propagating type wave motion in a much lower frequency range (0.01-0.05 Hz), produced by atmospheric pressure variations due to non-horizontal movements of air masses (Ziolkowski 1973). The third category involves propagating wave motion, originating naturally from distant sources like ocean waves impinging on coasts, storms on continental land mass and cyclones over deep sea regions. In such cases, Toksoz and Lacoss (1968), Capon (1969) and Lacoss et al (1969), found predominantly compressional wave propagation (0.5-1 Hz) and higher-mode Rayleigh wave (0.2-0.3 Hz). Earlier, Archambeau et al (1963) had also observed strong higher-mode Rayleigh-wave microseisms, at frequencies above 1 Hz. Microseismic noise, may be gaussian over short periods of time, but has superimposed on it other forms of noise (transients such as those of the Category 1 above) that exhibits spatial, as well as temporal variations at all sites.

ARRAY DESIGN ASPECTS

Measurement of phase velocity and dominant direction of microseisms is best accomplished, by setting up suitable arrays of seismic detectors (seismometers) on ground. The array configuration is guided by the range of wavelength of interest, carefully avoiding wave number aliasing, and keeping the inter element spacing smaller than those wavelengths, but its aperture larger than the longest wavelength to be resolved. Such an array, when combined with appropriate signal processing techniques, is capable of separating mixed Rayleigh-wave modes (fundamental and higher modes) and compressional wave, and propagation from multiple non-stationary sources. However, sufficiently small 2-D arrays can in general be successfully designed and configured for this purpose (Backus et al 1964). A variety of waveform processing techniques are available (see, for example, Bath 1974; Okada 2006), which can be employed depending on the objective. Recently, Arora (2009) worked out a novel approach, based on maximum entropy method (MEM) of spectral processing time series, demonstrating its superiority over some of the conventional methods, in cases where the periodicities of interest are of the same order, as the observational interval.

EXPANDING ARRAY CONFIGURATION

On account of logistical limitations it is usually unviable to establish large aperture seismic arrays in massive homogeneous rocky terrains stuffed with a large number of seismometers. These constraints essentially prompted to develop progressively expanding seismic arrays in which we have, to start with, only fewer seismometer stations (typically 3, 4, 5 or 7) at reasonably small inter-element spacing (Asten and Henstridge 1984). For example, a 3-station array can be set up with seismometers at locations 1, 2 and 3, and designated as Array-1 (Figure 1). After a few sets of recordings, station 1 is moved out to location 4 forming Array-2, for further recordings. Subsequently, station 2 is moved to location 5, and so on. The seismometers are thus shifted out progressively along the arrowed paths as shown in Figure 1 maintaining, of course, the basic array geometry (orthogonal linear cross).

A 4-element expanding array can likewise be constructed by emplacing another seismometer (either temporary or permanent) at location 0 (Figure 1). In Figure 2, we show how a 5-element array with seismometers at locations 0 to 4 (Array-1) initially can after some recordings be expanded to a bigger sized array for further recordings, without having to actually increase the number of seismometers. For example, when seismometers at locations 1 and 2 move to locations 5 and 6 respectively, we get Array-2; by further moving seismometer at location 3 to location 7 gives us Array-3; likewise, an Array-4 can be realized by further moving station 4 to some location 8; and so on. Thus, a step-by-step expansion can be made as desired to progressively augment a given basic array satisfying a whole range of requirements of studying various characteristics of seismic events including microseisms.

METHOD OF DATA PROCESSING WITH ILLUSTRATIONS

Following Asten and Hentsridge (1984), let us consider a wave source at infinite distance, from an array of N seismometers. We assume that, the waves have uniformly constant amplitude across the array. For multiple sources M, the amplitude at each of the N stations can be taken as the linear sum of the contributions, from all the sources. Thus, the complex amplitude Z_n at the n^{th} station at time t is given by:

$$Z_n = \sum_{j=1}^{M} A_j \exp\left[2\pi i\left(ft + k_j d_n\right)\right] \tag{1}$$

Where, k_j is the wave number from the j^{th} source, A_j is the amplitude from the j^{th} source of the plane waves of frequency f, and d_n is the displacement (spacing) of the n^{th} station, from the array origin. We also have $k_j = f / v$, v being the phase velocity. From the above expression (1), the set of amplitudes $Z_n\left(n = 1, 2, \cdots, N\right)$ are used to obtain a coherency matrix, which is subjected to a conventional two-dimensional wave number transform. Thus, a plane wave is represented as a vector in wave number space, oriented towards the source (Capon 1969).

Now, consider the case of a single stationary source of a 1 Hz – 2 km sec^{-1} plane wave. Since, lobe size of the array beam pattern is inversely proportional to the array size; the data acquired from a small array (e.g. a 3-station array) would yield only an approximate wave number estimate in this case. However, using relatively larger arrays (e.g. 5-station expanding arrays); more precise estimation of wave number is possible despite the presence of spurious peaks due to wave number aliasing on the wave number plots (Figures 3a-d). In cases of multiple sources, the limitations of smaller arrays are more apparent. For instance, if there are two sources of the same type of plane wave (1 Hz – 2 km sec^{-1}), separated by an azimuth of 120º, the wave number resolution is achieved reasonably well (Figure 4a) by the Array-3 configuration (refer Figure 2) of the 5-starion expanding array. Such an array is also capable of resolving two sources azimuthally much closer, being only 60º apart (Figure 4b), which is still better resolved, by overcoming any wave number aliasing, employing a bigger array (Figure 4c) like the Array-4 configuration (refer Figure 2).

It is evident that, using expanding array configurations as described above, vector velocity estimates at each frequency can be obtained for microseismic sources. At each frequency, estimates of apparent source azimuth of approaching microseisms are also determinable. A dynamic change in the azimuth of microseisms represents real movement of the principal microseismic source. Any observed scatter in the phase velocity and azimuth estimates are a function of statistical uncertainty in coherency and the limitation of the array configuration employed, particularly if data are acquired from smaller arrays (e.g. 3-station array). There is also a possibility of clustering of velocity moduli in certain frequency bands due to either or all of the following reasons: (i) extreme biasing owing to multiple sources of comparable strength, (ii) dominance of non-propagating microseisms generated by atmospheric loading effects, and (iii) presence of two or more modes of Rayleigh wave propagation.

DISCUSSION AND CONCLUSIONS

The usefulness of a simple 3-station array is limited to situations where a single microseismic source is dominant, even though weak multiple sources may exist. The response of such small array can be somewhat ambiguous unless the source azimuth is known. Therefore, a relatively larger expanding array with proportionately larger spatial sampling is a preferred choice, which overcomes several limitations in resolving sources. In consistency with this view, a 5-station expanding array is capable of resolving multiple sources with predictable wave number estimation. A 4-station expanding array can also resolve multiple sources but may produce somewhat biased estimates in frequency-wave number (*f-k*) space.

It is generally possible to reduce or minimize interference due to randomly oriented cluster of sources by taking short data lengths. However, this may give rise to greater statistical uncertainty of phase relations and, therefore, of vector velocity estimates across a given array.

In order to achieve high resolution of wave number in the frequency-wave number analysis, it is necessary to take recourse to adequate spatial sampling of data from an appropriately configured array in expanding mode.

Using microseismic data including phase velocity and azimuth acquired from an expanding array of optimum size, structure of crustal sediments beneath the array site can be inferred from the phase velocity dispersion. Further, deployment of 3-component (two horizontal and one vertical) seismometers instead of only vertical-component ones in any suitable array configuration would enable particle motion studies for proper identification of wave propagation modes in microseisms.

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APPENDICIES

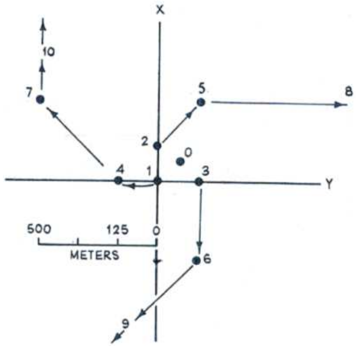

Figure 1: Illustration of a 3-Seismometer Expanding Array Configuration. Stations at Locations 1, 2 and 3: Array-1; Stations at Locations 2, 3 and 4: Array-2; Stations at Locations 3, 4 and 5: Array-3; and so on. Similarly, a 4-Element Expanding Array Can Be Realized by emplacing a Fourth Seismometer, either Temporary or Permanent, at Location 0

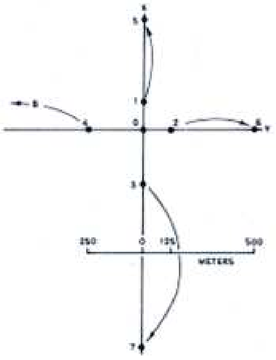

Figure 2: Illustration of a 5-Seismometer Expanding Array Configuration. Stations at Locations 0, 1, 2, 3 and 4: Array-1; Stations at Locations 0, 3, 4, 5 and 6: Array-2; Stations at Locations 0, 3, 5, 6 and 7: Array-3; Stations at Locations 0, 5, 6, 7 and 8: Array-4; and so on

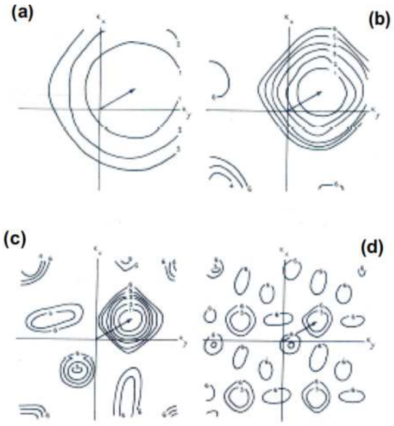

Figure 3: Wave number Plots in Response of a 5-Station Expanding Array to a Single Source of a 1 Hz – 2 km/sec Plane Wave Using: (a) Array-1, (b) Array-2, (c) Array-3, and (d) Array-4, Conforming to Four Different Configurations Shown in Figure 2. All Contours are labeled in dB Relative to Maximum

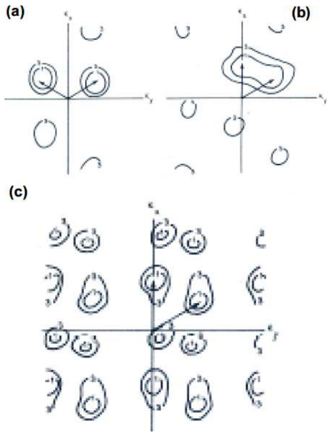

Figure 4: Wavenumber Resolution, Employing a 5-Seismometer Expanding Array in the Array-3 Configuration (Refer Figure 2), of Two Sources of a 1 Hz – 2 km/sec Plane Wave When Their Azimuthal Separation is (a) Farther (120^{o}), and (b) Closer (60^{o}); Further Improvement in Wavenumber Resolution for the Closer Pair of Sources Obtained using the Array-4 Configuration (Figure 2) is Shown in the Panel; (c) All Contours are Labeled in dB Relative to Maximum