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Three Dimensional Noise Field Estimation from Horizontal Line Arrays

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ABSTRACT

A technique to estimate the three dimensional (3-D) character of the undersea ambient noise field with the use of a horizontal line array as the measurement tool has been developed. Horizontal line array beam noise data, on several array headings, and knowledge of the array's 3-D beam response patterns were used as an input into the 3-D noise field estimation technique. The final product indicates that the resulting 3-D noise field estimate can be used to determine both the horizontal and the vertical directionality of the noise field. Furthermore, having an estimate of the 3-D noise field facilitates other investigations of the noise field that are normally not possible with either a vertical or a horizontal line array, such as the vertical directionality of the noise in a small azimuthal sector or the horizontal directionality at a particular elevation angle. It also appears that the use of horizontal line arrays and this 3-D technique could provide necessary measurement inputs to support design of volumetric array systems without the expense and/or technical difficulty of deploying a volumetric array.

INTRODUCTION

An algorithm to estimate the three dimensional (3-D) ambient noise field has been developed that utilizes horizontal line array beam noise data on multiple array headings as the basic data input. Several measurement/processing techniques have been developed to estimate the horizontal directionality of ambient noise from horizontal line arrays[1,2]. In most cases, the 2-D representation of the array beam pattern is adequate to accurately estimate the horizontal directionality[1]. When significant amounts of the noise are distributed at elevation angles well off the zero elevation angle, use of the 3-D structure of the beam patterns and a priori information about the noise vertical arrival structure greatly improve only the estimate of the horizontal directionality (2-D noise field)[2]. Unfortunately, the 3-D noise field is not estimated by this latter technique. When the vertical directionality component of the noise changes as a function of azimuth, as is generally the case when shipping noise is an important contribution, the true 3-D, conical, beam response pattern needs to be implemented so that the noise energy will be accurately distributed in elevation as well as in azimuth. The technique/algorithm described herein is an iterative process that uses the true 3-D, conical nature of the horizontal line array beam response pattern during the ambient noise directionality calculation.

In order to formulate the ambient noise 3-D estimation technique, the primary equation that transforms the spherical coordinates of the noise field into the conical coordinate of the array will be presented. The formulation of the technique is provided in a sufficiently general nature to handle deviations from the array axis including an arbitrary array tilt. Finally, actual results from a recent at-sea measurement experiment will be shown to demonstrate the capability of the 3-D ambient noise estimation technique.

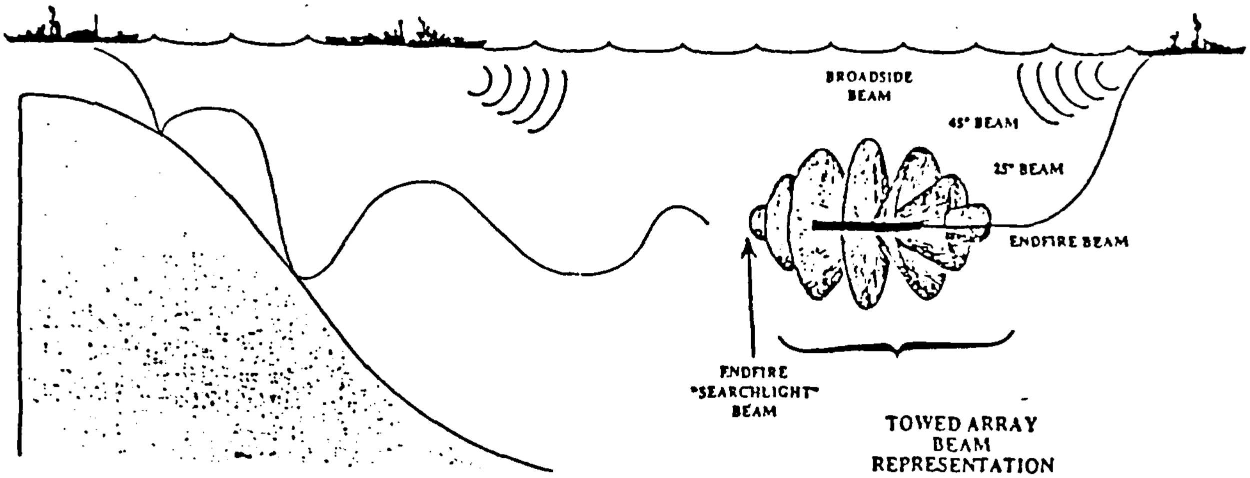

Figure 1. Representation of a towed horizontal line array measuring undersea ambient noise.

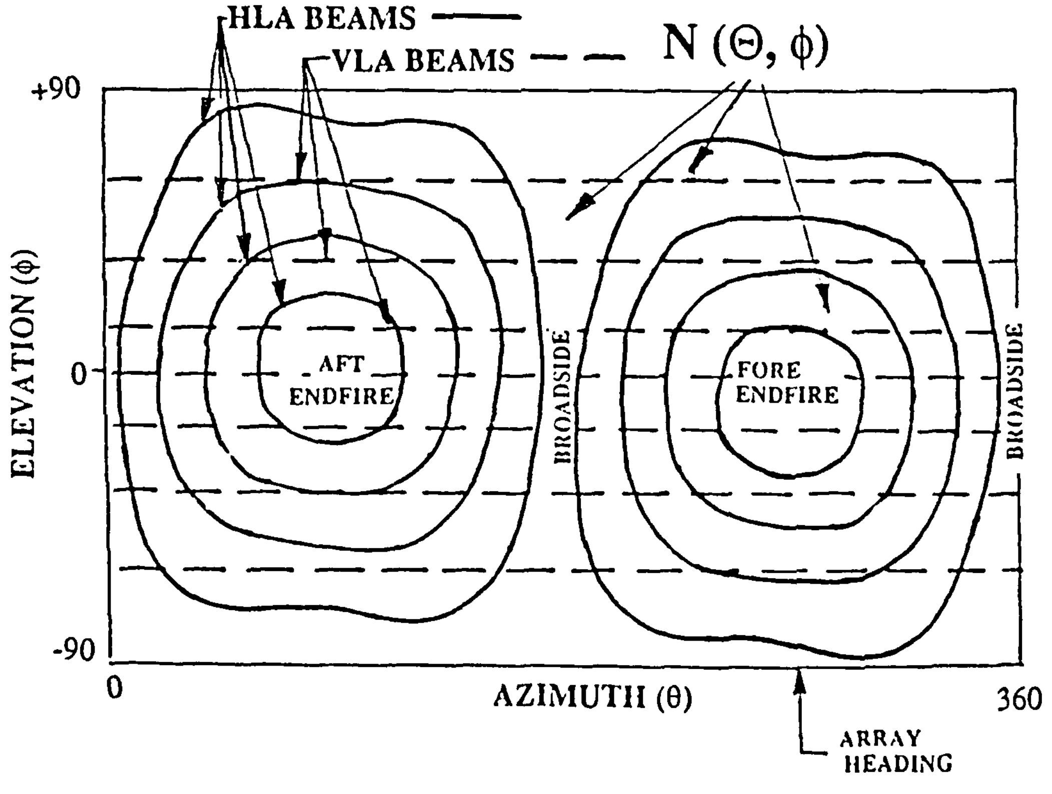

Figure 2. Representation of a spherical noise field N(Θ, ϕ) and the conical "footprints" of the vertical line array (VLA) and the tilted horizontal line array (HLA) on a plane surface.

BACKGROUND

The line array, because of its relatively low cost and ease of deployment, is often used to measure the undersea ambient noise. Furthermore, the towed horizontal line array with its added advantage of mobility has achieved a high degree of utilization by researchers. The major disadvantage of the line array is that it can only distinguish the acoustic arrival angle relative to the axis of the array. It cannot uniquely determine the spherical coordinates of the sound. The resulting ambiguity in angle of arrival describes a cone with apex at the center of the array and its center axis oriented along the axis of the array. The arrival angle of the sound relative to the array axis is half of the cone apex angle. This is illustrated by the representation of the towed array in Figure 1 and the superimposed 3-D beam response patterns. Because of the vertical stratification of the acoustic propagation field in the ocean, the various beams of the line array sample different noise field and acoustic propagation regimes, i.e. SOFAR channel (RRR) and boundary interacting (RSR).

The complex nature of the coupling of the reception characteristics of the line array (conical beams) with the spherical structure of the noise field is partially illustrated by Figure 1. However, it is illustrated better in Figure 2 in which the noise sphere is represented as a flat surface and the beam response "footprints" of both a horizontal line array on a heading of 270° with a few degrees of array tilt (solid curves) and a vertical line array (dashed horizontal lines) have been superimposed. Only the footprints of the horizontal line array have both elevation and azimuth angle dependencies. Therefore, it should be possible to estimate both azimuth and the elevation angle dependence of the noise from horizontal line array data when measurements are made on several different headings. A slight tilt of the array as illustrated in Figure 2 is desireable to eliminate upward-downward ambiguities. It is very difficult to balance the array well enough that it always tows perfectly horizontal. Hence, some degree of tilt is a natural consequence of the measurement process.

The undersea ambient noise field at a given location can be expressed as a function of time and spherical angles in the following form:

$$N(\Theta, \phi, t) = N(\Theta, \phi) + \mu(\Theta, \phi, t) + \varepsilon(\Theta, \phi, t)$$

where

t = time

Θ = azimuth angle in spherical coordinates

ϕ = elevation angle in spherical coordinates

$N(\Theta, \phi, t)$ = measured noise power at a given frequency

$N(\Theta, \phi)$ = pseudostationary background ambient noise

$\mu(\Theta, \phi, t)$ = time dependent component of the ambient noise due to fluctuation in propagation, noise source movement, changes in noise source levels.

$\varepsilon(\Theta, \phi, t)$ = errors in measurements due to flow noise, non- straight array, calibration errors, etc.

In an ideal measurement $\varepsilon(\Theta, \phi, t)$ is eliminated. Various measurement and data processing techniques have been developed to minimize its effects in the results. $\mu(\Theta, \phi, t)$ can be ignored if only the pseudostationary component $N(\Theta, \phi)$ is desired. It is the pseudostationary component that can be expected to repeat on a seasonal basis year after year, when the noise source distributions and acoustic propagation conditions are again the same. It is this term that can be

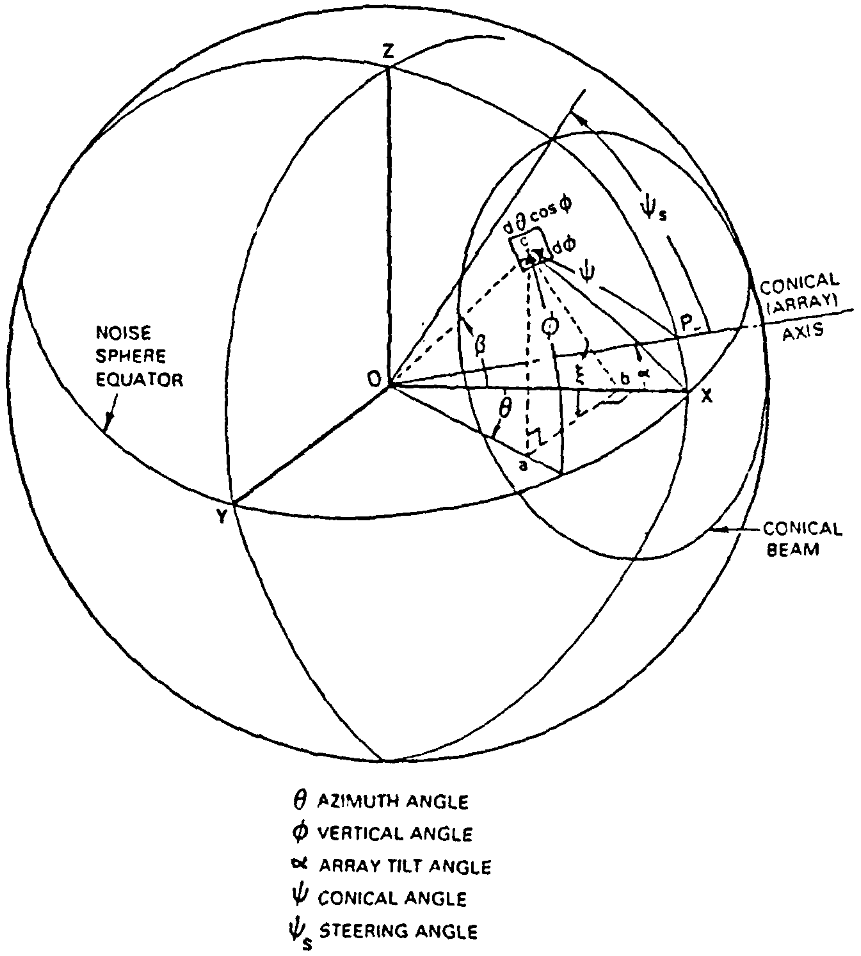

Figure 3. Coordinate system for the noise sphere and the conical beams of the line array.

used in the predictions of the noise for future times, and it is this term which the technique presented herein attempts to estimate.

The technique for estimating $N(\Theta, \phi)$ is based on beam noise data measured by a horizontal line array. This can be expressed mathematically as:

$$R_{i,j} = 1/T \int_{0}^{T} dt \int_{0}^{2\pi} d\Theta \int_{-\pi/2}^{\pi/2} N(\Theta, \phi, t)\, b_i\, (\Theta - \Gamma_{j,}, \phi) \cos \phi \, d\phi$$

where

$R_{i,j}$ = beam output noise powers averaged over a time T
i = beam number
j = array heading number
Γ_j = the array heading angle
$b_i\, (\Theta, \phi)$ = power response of ith beam

APPROACH

The horizontal line array can determine the arrival angle X of a signal relative to the axis (or line) of the array, but it cannot determine the absolute orientation in space. Hence, all orientations give the same response as long as the arrival angle relative to the array axis is the same. The resulting beam response pattern is conical, which intersects a concentric sphere in a circle as illustrated in Figure 3. The noise field on the other hand, is more naturally described in terms of spherical coordinates. The mathematical representations of the conical beams of the line array and the spherical nature of the noise field are basically incompatible. This incompatibility must first be overcome before an efficient algorithm can be developed to estimate the spherical noise $N(\Theta, \phi)$ from conical data $R_{i,j}$. This incompatibility is overcome by the following transformation which transforms the noise power at spherical angles Θ and ϕ into noise at the conical angle β:

$$\beta = \cos^{-1} \{\cos \Theta \cos \phi \cos X + \sin [\cos^{-1} (\cos \Theta \cos \phi)] \sin X \sin [\tan^{-1} (\sin \phi / \cos \phi \sin \Theta)]\} \qquad (3)$$

The estimation of $N(\Theta, \phi)$ is an iterative one that begins with assuming an estimated noise field $N_o(\Theta, \phi)$. The simplest possible form is a constant, which corresponds to an isotropic noise field (e.g. $N_o(\Theta, \phi) = C$). Next $N_o(\Theta, \phi)$ is convolved with the beam patterns of the array, using equation (3), to get estimates $R'_{i,j}$, for $R_{i,j}$. The differences $D_{i,j} = R_{i,j} - R'_{i,j}$ are used to either add noise to or subtract noise from $N_o(\Theta, \phi)$ at the appropriate locations Θ and ϕ. When this has been done for all i beams and j array headings, a new estimate $N_1(\Theta, \phi)$ has been created. This process of convolution and noise field modification is continued until the differences fall below a predetermined threshold and then the final noise field estimate $N_f(\Theta, \phi)$ is accepted as the estimation for $N(\Theta, \phi)$.

RESULTS

Beam noise data from a line array on different headings in the undersea ambient noise field were processed by the 3-D noise field estimation algorithm. The results are presented in Figure 4. The noise levels as a function of elevation angle ϕ and azimuth angle Θ are plotted in gray scale contours with the level increasing with darkness. The horizontal directionality of the noise $N(\Theta)$ is the quantity that a 2-D estimation algorithm would attempt to generate. In the case of the 3-D noise field, it can be obtained by merely summing over all vertical angles ϕ at a given azimuth angle Θ (bottom plot in Figure 4). The curves in the rectangular plot to the right in Figure 4 are vertical profiles of the total noise and of two small azimuthal sectors, one in a direction of high level noise (Θ = 290 deg) and one in a direction of low level noise(Θ = 150 deg). The vertical profile of the total noise is generally obtained from measurements by a vertical line array. In this case, it was obtained by summing over all azimuth angles Θ at each elevation angle ϕ. The other two vertical profiles are for sectors that could not be measured by either a vertical line array or a horizontal line array. In fact, the measurement of those profiles would normally require a high resolution volumetric array, something that presently does not exist.

SUMMARY/CONCLUSIONS

A technique for using horizontal line array beam noise data measured on multiple headings of the array has been developed. It utilizes an iterative technique that compares measured beam noise data with corresponding results obtained from convolving the beam noise patterns with an estimate of the 3-D noise field to guide modifications of the noise field estimate. Once the final estimate is obtained, it is then possible to investigate characteristics of the noise field that are essentially invisible to the array that acquired the original beam noise data, such as the vertical directionality of the noise azimuthal sectors that otherwise would require a high resolution volumetric array to measure.

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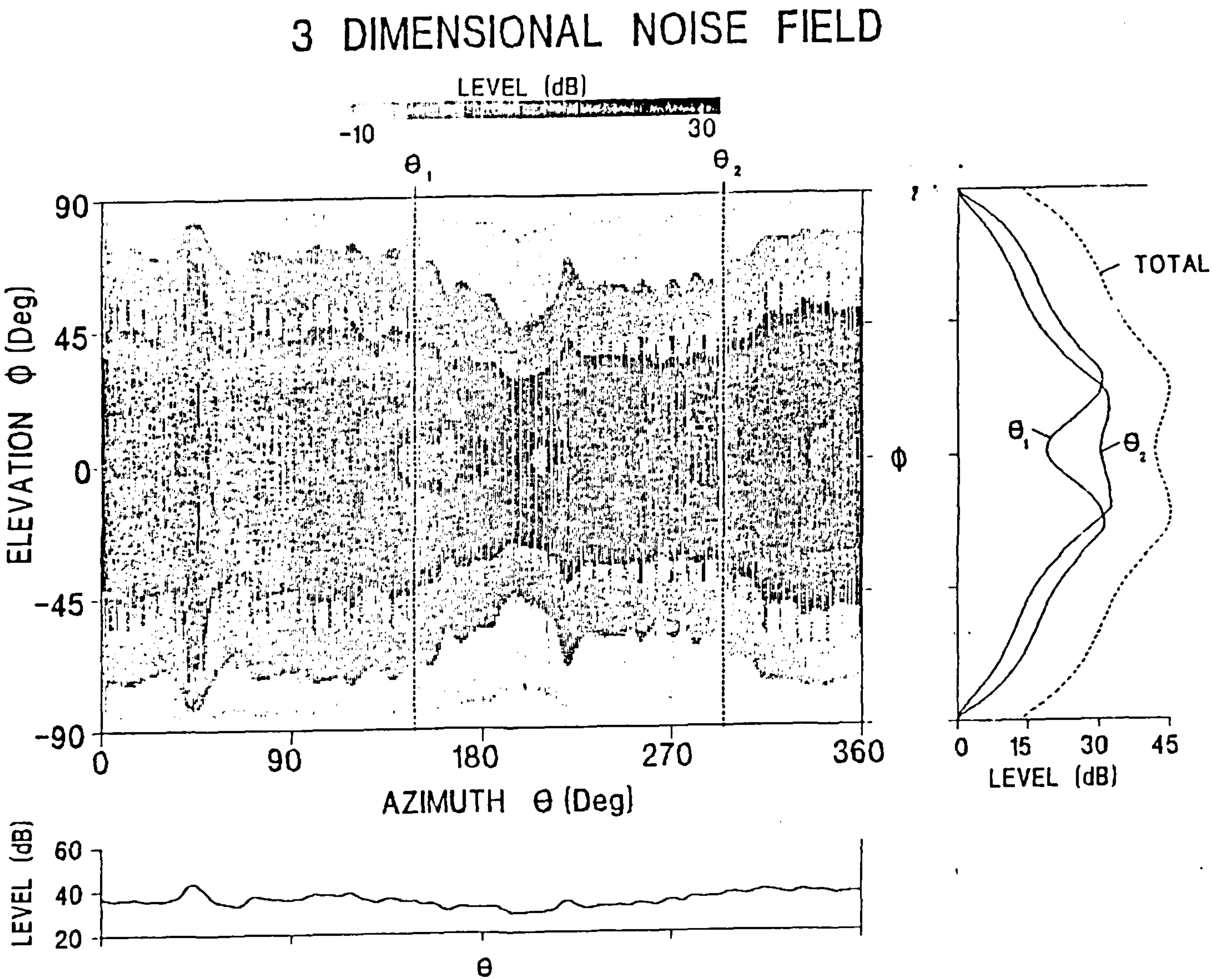

Figure 4. 3-D noise field estimate (gray scale contour plot) with corresponding 2-D horizontal directionality (bottom) and vertical profiles for the total noise and two small azimuthal sectors, one noisy (Θ_2) and one quiet (Θ_1).