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Applications of a Motion Compensation Stabilized Vertical Array of Hydrophones

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ABSTRACT When a vertical array of hydrophones is used to determine the location of a submerged acoustic source in the ocean, performance is limited by the quality of the data, especially when there is interference from ambient noise and other sources or when there are uncertainties in the parameters of the environment. High-quality data may be obtained by anchoring a vertical array on the seafloor, but this time-consuming approach does not allow frequent deployments and mobility. By using motion compensation to eliminate the vertical motion of an array that is deployed from a surface platform, it may be possible to obtain high-quality data with a rapidly deployable system. Other applications that could benefit from this capability include the geoacoustic inverse problem of estimating the parameters of the sediment and studying the effects of horizontal diffraction and horizontal multi-paths for global-scale problems.

INDEX TERMS Ocean acoustics, hydrophones, vertical arrays, motion compensation, active heave compensation, signal processing, source localization, inverse problems, azimuthal coupling.

I. INTRODUCTION

Various types of arrays of hydrophones have been utilized in ocean acoustics. Horizontal arrays may be mounted on the ocean bottom or towed behind a ship. They are often used to determine the bearing of an acoustic source, but a towed array may also be used to determine the properties of ocean sediments [1]–[3]. Due to the phenomenon of multipath propagation, the acoustic field on a vertical array in a waveguide may contain much more information about the location of a source than would be received on an array located in free space [4], [5]. It may be possible to determine the location of a source even when the signal is buried in noise [6], [7], there is interference from multiple sources [8], and there are uncertainties in the sound speed and other parameters of the environment [9], [10]. Acoustic data from a vertical array may also be used to determine the layering and acoustic parameters of the sediment [11].

The quality of acoustic data on a vertical array and the performance of techniques that extract information from such data may be substantially degraded by surface motion when the deployment is from a floating platform. For this reason, vertical arrays are often deployed with the array attached at its bottom end to an anchor mooring that rests on the seafloor and at its top end to a submerged float as shown in Fig. 1. Such bottom-mounted vertical arrays are limited to relatively narrow ranges of bathymetry, and their deployment and recovery are complicated and time consuming; these factors preclude frequent deployments. Various applications in ocean acoustics would benefit from an approach for deploying a vertical array from a surface platform that is immune to the effects of surface motion and efficient enough to allow frequent deployments.

For a vertical array that is suspended from a mounting point on a surface platform, it may be possible to treat the array as a rigid object when surface waves cause the mounting point to ascend; but even this simple type of motion may be sufficient to severely degrade acoustic data; when the mounting point descends, there may be relative motion between the individual hydrophones. A spar buoy may be used to reduce the effects of surface motion [12], [13], but it would be beneficial to eliminate the motion entirely. It should be possible to use motion compensation (or active heave compensation) [14] to eliminate the vertical motion of a vertical array with a configuration such as the one shown in Fig. 2.

The capability to rapidly deploy a stabilized vertical array from a ship would be very useful, and the approach may be feasible even on smaller platforms. Since the objective of preventing vertical motion does not require work against gravity, the power requirements of a motion compensation system should be minimal; it might be possible to design such a system to run off batteries on an autonomous buoy.

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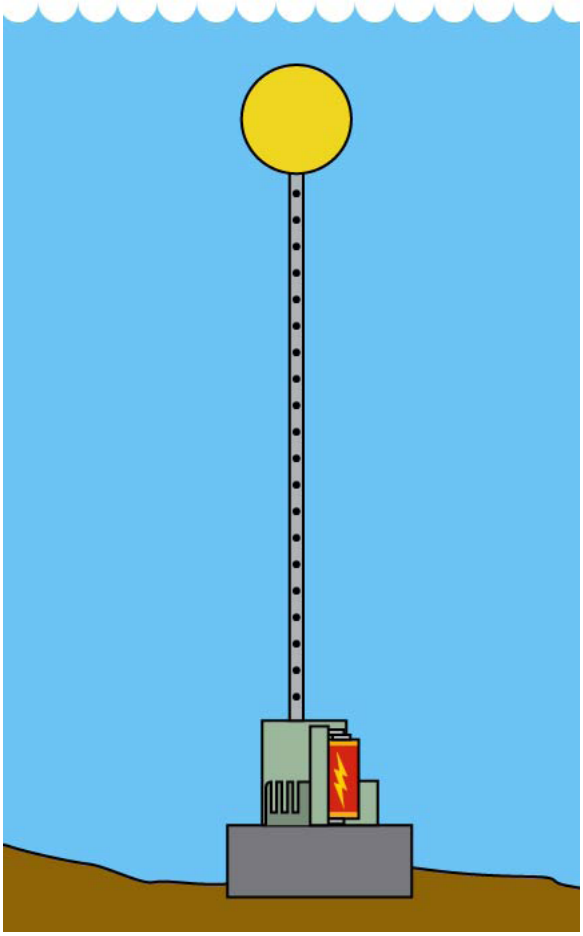

FIGURE 1. Bottom mounted vertical array of hydrophones.

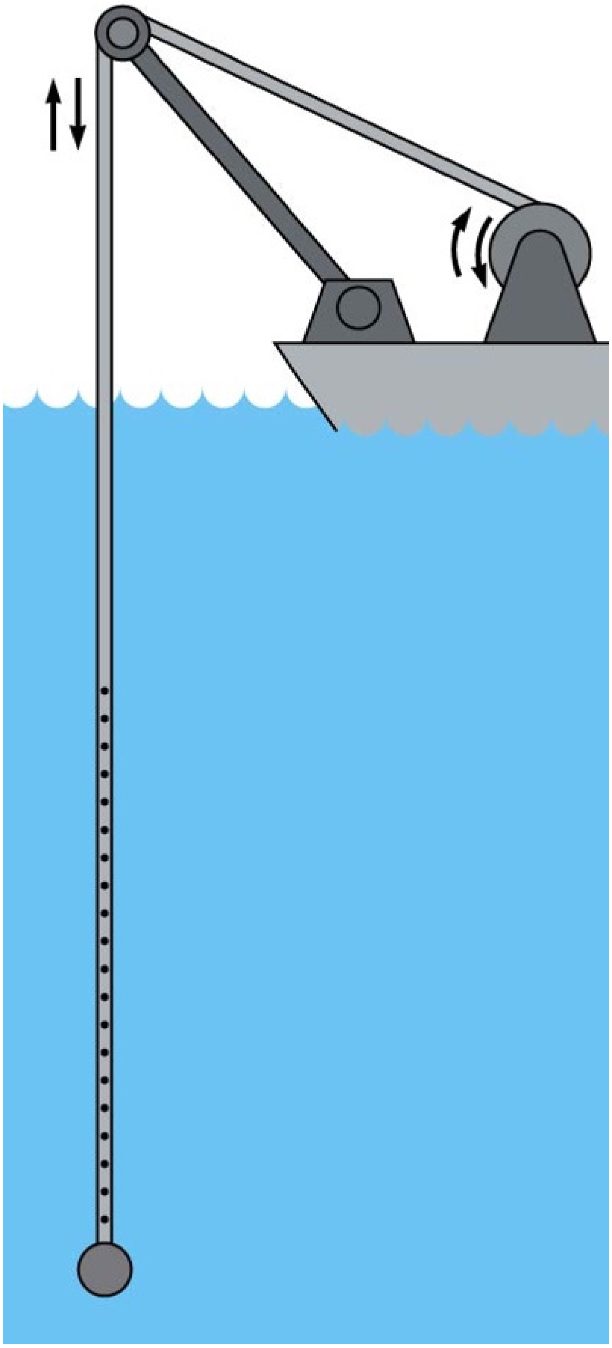

FIGURE 2. Motion compensation stabilized vertical array of hydrophones. The winch is used to actively prevent vertical motion of the cable.

The purpose of this paper is to consider some of the applications that could potentially benefit from a motion compensation stabilized vertical array of hydrophones.

When an array of hydrophones is deployed from a ship, there is a possibility of interfering noise from the engines and other sources, but this factor may be reduced by stopping the engines and other machines while taking data. Even if there is some noise from the ship, it would arrive from nearly directly above and would therefore be easy to distinguish from a signal from a distant source of interest that propagates within a relatively small angle of the horizontal.

II. SOURCE LOCALIZATION

It is often possible to determine the location of an acoustic source by computing the correlation between the data on the array and solutions of the wave equation that correspond to a point source at a test location. In the most basic form of this matched-field processing (MFP) approach, the test source is moved through the environment, and an estimate for the location of the source corresponds to the location of the main peak in the correlation function. There are some applications for which the array configuration in Fig. 1 is useful for MFP, but mobility would be a useful capability for some applications, such as tracking sea mammals or searching for a source over a wide area.

MFP may fail when the signal-to-noise ratio (SNR) is low [6]–[8] or when there are uncertainties in the parameters of the environment [9], [10], such as the ocean depth (a function of the horizontal coordinates), the sound speed in the ocean (a function of all three coordinates), and the parameters of the sediment (layer thicknesses, wave speeds, density, etc.). The performance of MFP also depends on the quality of the data, which are used to generate the covariance

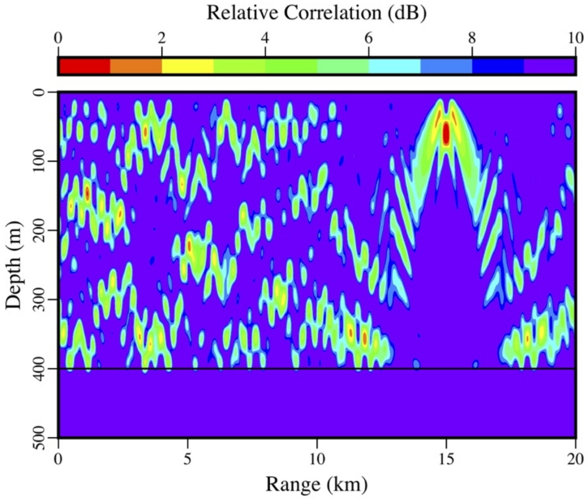

FIGURE 3. Ambiguity surface for a 50 Hz source located at a range of 15 km and a depth of 60 m in a shallow water waveguide.

matrix [4], [5]. In order to obtain a high-quality estimate of the covariance matrix, the data must be Fourier transformed and averaged over sufficient intervals of time. Even relatively small motions may result in degradations that are sufficient to cause MFP to fail when the SNR is low or there are uncertainties in the environment. For these cases, a stabilized vertical array would be particularly useful.

The breakdown of MFP due to array motion is related to the problem of photographic blurring due to camera motion when long exposure times are required in order to handle low light levels. MFP is based on the construction of an ambiguity surface [5] in which the most intense peak may be regarded as an image of the source when the approach is successful. For the example appearing in Fig. 3, the main peak corresponds to a 50 Hz source at a range of 15 km and a depth of 60 m. If the array were to move horizontally, the image of the source would also move horizontally, and there would be a series of images blurred together. For other types of motion, there would be a more complex degradation of the image of the source. On land, photos of faint objects, such as auroras, are often obtained by using long exposures with a camera that is mounted on a tripod, but this approach is of limited use on a moving platform. The photos of auroras in Fig. 4 were obtained on a moving ship using long exposures with a hand-held camera that is stabilized with a gimbal. Due to the motion of the ship, multiple images of nearby items appear in two of the photos. If the camera had been mounted on a tripod, the nearby items would be clear, but the auroras would be blurred. By using motion compensation to stabilize a vertical array, it might similarly be possible to obtain a correlation function that has a well-defined image of the source.

We illustrate the degradations caused by array motion for a 500 Hz ocean acoustics problem in which the ocean depth is 300 m. The sound speed is 1500 m/s in the ocean and 1700 m/s in the sediment, which has a density of 1.5 g/cm^3 and attenuation of 0.5 dB per wavelength. The source is at a depth of 50 m and the array of hydrophones is located at a range of 5 km and spans $30 < z < 130$ m. The array has horizontal and vertical motions that are sinusoidal with a period of 5 s. The vertical amplitude is the same for all of the hydrophones. The horizontal amplitude decreases linearly with depth from half the vertical amplitude at the top hydrophone to a quarter the vertical amplitude at the bottom hydrophone. A parabolic equation model [15] was used to simulate acoustic time series on the moving hydrophones. The complex pressure, which appears in Fig. 5 for two cases, was obtained by taking the Fourier transform of the time series over 20 s. For a vertical amplitude of 0.5 m, the motion causes small errors in the complex pressure, which may be sufficient for MFP to break down when the SNR is low. For a vertical amplitude of 1.0 m, the motion causes large errors in the complex pressure, which may be sufficient for MFP to break down even when the SNR is high.

FIGURE 4. Photos of auroras that were obtained using long exposures (approximately 20 s) with a DJI Osmo+ on a moving ship. Movements of parts of the ship are evident in the two lower images, which were affected by moonlight.

III. GEOACOUSTIC INVERSION

Data from a vertical array may also be used to determine the layer structure and parameters of the sediment.

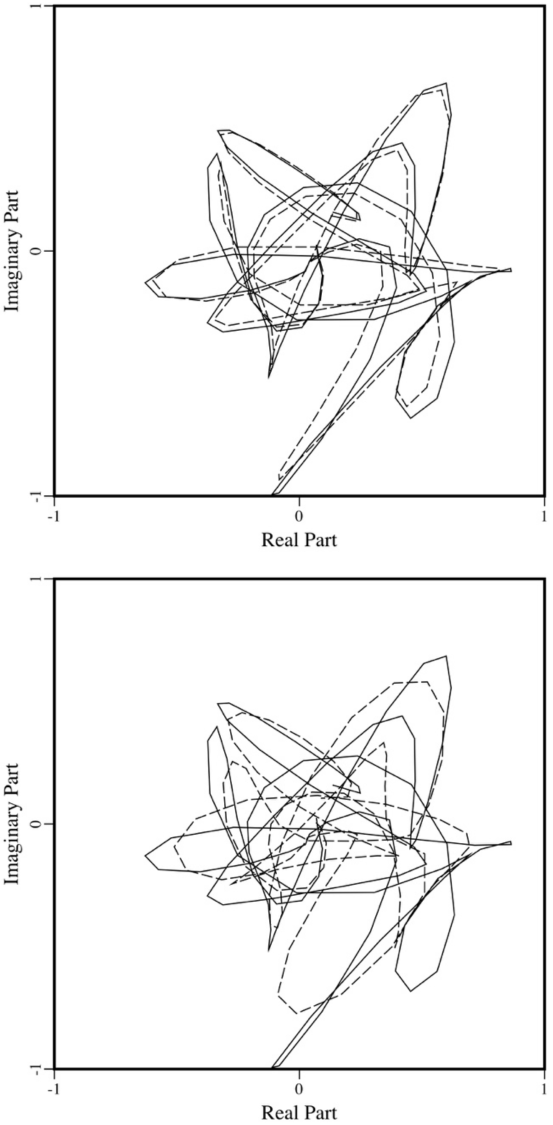

FIGURE 5. Complex pressure (normalized to unit amplitude) on vertical arrays that are fixed (solid curves) and moving (dashed curves). The vertical amplitude of the array motion is 0.5 m for the top graph and 1.0 m for the lower graph.

For this application, the array configuration in Fig. 1 would be ineffective for estimating sediment parameters beyond the vicinity of the array. With a rapidly deployable array, a large area could be surveyed by repeatedly deploying the source and the array and performing geoacoustic inversion for each deployment as shown in Fig. 6. This approach requires two ships, with the source and the array both stabilized using motion compensation.

The horizontal distance between the source and the array may be varied in order to increase the sensitivity of the acoustic field on the array to the desired sediment parameters [16]. Relatively short separations tend to be more effective for probing deep into the sediment and may allow a smaller number of parameters (e.g., it may be possible to use linear approximations for the ocean depth and thickness of the sediment layer in Fig. 6 over short range intervals). For longer separations, the acoustic field may be more sensitive to the parameters of the upper sediment layer.

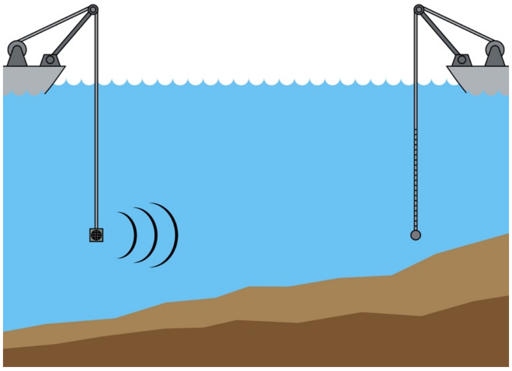

FIGURE 6. Experimental configuration involving a source and array that are both stabilized by motion compensation. The rapid deployment capability would make it possible to repeatedly perform geoacoustic inversion of relatively short intervals in order to survey a large area.

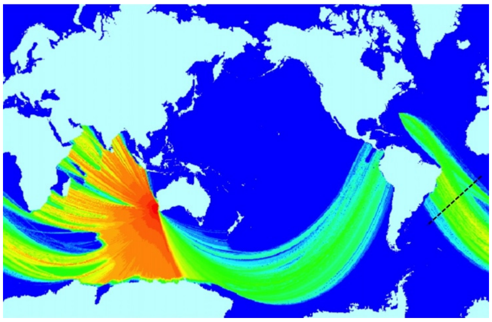

FIGURE 7. Horizontal multi-paths for a problem related to the Perth-to-Bermuda experiment [17] that was solved using an approximate method [19]. This problem could be studied experimentally with multiple deployments of a stabilized array along the path marked by a dashed line.

IV. GLOBAL-SCALE OCEAN ACOUSTICS

Most existing arrays are designed to sample the acoustic field in the horizontal or the vertical but not both. With a stabilized vertical array that could be rapidly deployed, it would be feasible to sample the acoustic field in both the horizontal and the vertical. There are problems in global-scale ocean acoustics for which a stabilized vertical array would be useful for studying three-dimensional effects. During a global-scale experiment in 1960, explosive charges were detonated off the coast of Perth, Australia, and two main arrivals were detected off the coast of Bermuda [17]. With current technology, it is not practical to model global-scale acoustic propagation in three dimensions, but the method of adiabatic modes has been used to obtain approximate solutions of this problem [18], [19]. Those calculations are consistent with the experiment in that they predict two main propagation paths, but the accuracy of the adiabatic mode solution has not been validated for global-scale problems.

As shown in Fig. 7, it might be possible to gain a better understanding of the Perth-to-Bermuda propagation paths by

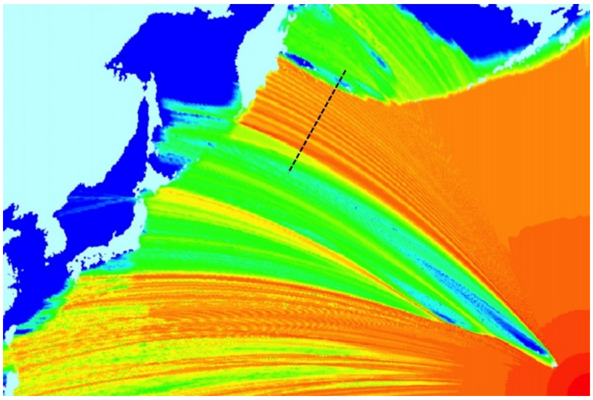

FIGURE 8. **Horizontal diffraction by the Hawaiian Islands in an approximate solution [19]. This problem could be studied experimentally with multiple deployments of a stabilized array along the path marked by a dashed line.**

repeating the experiment and deploying a stabilized array at several locations along the dashed path. The method of adiabatic modes has also been used to obtain approximate solutions for problems involving horizontal diffraction by islands and other bathymetric features [19]. As shown in Fig. 8, it might be possible to gain a better understanding of such a global-scale diffraction problem by repeatedly deploying a stabilized array.

V. DISCUSSION

Due to the time required to deploy a bottom-mounted array, multiple deployments are usually not practical during an experiment, and such deployments become increasingly difficult as the local ocean depth increases. A motion compensation stabilized vertical array could be deployed rapidly and frequently in water of any depth. The mobility of such an array would be useful for applications such as source localization, geoacoustic inversion, and sampling the acoustic field in large scale-problems involving horizontal multi-paths and horizontal diffraction. Various motion compensation (or active heave compensation) approaches have been developed for marine applications. It would be useful to develop such an approach for vertical arrays of hydrophones. Since no work is done against gravity, such a system should have modest power requirements and might therefore be feasible on an autonomous buoy. Active heave technology has been developed for cranes that are designed for lifting heavy loads at sea. A vertical array of hydrophones is a much lighter load, especially when submerged. It should be possible to scale this technology down to an easily portable device that would be applicable to array deployment systems that are currently in use. Such a device could have a significant impact in many ocean acoustics experiments.

REFERENCES

[1] W. Kuperman, M. Werby, K. Gilbert, and G. Tango, "Beam forming on bottom-interacting tow-ship noise," *IEEE J. Ocean. Eng.*, vol. 10, no. 3, pp. 290–298, Jul. 1985.

[2] M. Siderius, P. L. Nielsen, and P. Gerstoft, "Range-dependent seabed characterization by inversion of acoustic data from a towed receiver array," *J. Acoust. Soc. Amer.*, vol. 112, no. 4, pp. 1523–1535, 2002.

[3] T. C. Yang, K. Yoo, and L. T. Fialkowski, "Subbottom profiling using a ship towed line array and geoacoustic inversion," *J. Acoust. Soc. Amer.*, vol. 122, pp. 3338–3352, Sep. 2007.

[4] H. P. Bucker, "Use of calculated sound fields and matched-field detection to locate sound sources in shallow water," *J. Acoust. Soc. Amer.*, vol. 59, pp. 368–373, Feb. 1976.

[5] A. B. Baggeroer, W. A. Kuperman, and P. N. Mikhalevsky, "An overview of matched field methods in ocean acoustics," *IEEE J. Ocean. Eng.*, vol. 18, no. 4, pp. 401–424, Oct. 1993.

[6] M. D. Collins, N. C. Makris, and L. T. Fialkowski, "Noise cancellation and source localization," *J. Acoust. Soc. Amer.*, vol. 96, pp. 1773–1776, May 1994.

[7] M. D. Collins, R. N. Baer, and H. J. Simpson, "Experimental testing of the noise-canceling processor," *J. Acoust. Soc. Amer.*, vol. 130, pp. 1217–1221, Jul. 2011.

[8] M. D. Collins, L. T. Fialkowski, W. A. Kuperman, and J. S. Perkins, "The multivalued Bartlett processor and source tracking," *J. Acoust. Soc. Amer.*, vol. 97, pp. 235–241, Jul. 1994.

[9] M. D. Collins and W. A. Kuperman, "Focalization: Environmental focusing and source localization," *J. Acoust. Soc. Amer.*, vol. 90, pp. 1410–1422, Apr. 1991.

[10] R. N. Baer and M. D. Collins, "Source localization in the presence of gross sediment uncertainties," *J. Acoust. Soc. Amer.*, vol. 120, no. 2, pp. 870–874, 2006.

[11] M. D. Collins, W. A. Kuperman, and H. Schmidt, "Nonlinear inversion for ocean-bottom properties," *J. Acoust. Soc. Amer.*, vol. 92, no. 5, pp. 2770–2783, 1992.

[12] F. H. Fisher and F. N. Spiess, "Flip-floating instrument platform," *J. Acoust. Soc. Amer.*, vol. 35, no. 10, pp. 1633–1644, 1963.

[13] J. Halkyard and E. H. Horton, "Spar platforms for deep water oil and gas fields," *Marine Technol. Soc. J.*, vol. 30, no. 3, pp. 3–12, 1996.

[14] J. K. Woodacre, R. J. Bauer, and R. A. Irani, "A review of vertical motion heave compensation systems," *Ocean Eng.*, vol. 104, pp. 140–154, Aug. 2015.

[15] M. D. Collins, R. J. Cederberg, D. B. King, and S. A. Chin-Bing, "Comparison of algorithms for solving parabolic wave equations," *J. Acoust. Soc. Amer.*, vol. 100, no. 1, pp. 178–182, 1996.

[16] M. D. Collins and L. Fishman, "Efficient navigation of parameter landscapes," *J. Acoust. Soc. Amer.*, vol. 98, no. 3, pp. 1637–1644, 1995.

[17] R. C. Shockley, J. Northrup, P. G. Hansen, and C. Hartdegen, "SOFAR propagation paths from Australia to Bermuda: Comparison of signal speed algorithms and experiments," *J. Acoust. Soc. Amer.*, vol. 71, no. 1, pp. 51–60, 1982.

[18] K. D. Heaney, W. A. Kuperman, and B. E. McDonald, "Perth–Bermuda sound propagation (1960): Adiabatic mode interpretation," *J. Acoust. Soc. Amer.*, vol. 90, no. 5, pp. 2586–2594, 1991.

[19] M. D. Collins, B. E. McDonald, K. D. Heaney, and W. A. Kuperman, "Three-dimensional effects in global acoustics," *J. Acoust. Soc. Amer.*, vol. 97, no. 3, pp. 1567–1575, 1995.

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