Propagation of How-Frequency, Transient Acoustic Signals through a Fluctuating Ocean: Development of a 3D Scattering Theory and Comparison with NPAL Experimental Data

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LONG-TERM GOALS

Development of a new, 3D, modal theory of low-frequency, long-range sound propagation through a fluctuating ocean, including both CW and transient acoustic signals.

Comparison of theoretical and numerical results with NPAL experimental data.

OBJECTIVES

To develop a 3D modal theory of broadband sound propagation though a fluctuating ocean, including analysis of the coherence function for transient acoustic signals and temporal coherence.

To develop computer codes for calculation of the horizontal and vertical coherence functions of transient acoustic signals and temporal coherence.

To compare theoretical and numerical results with the 1998-1999, 2004, and 2009-2011 (in the Philippine Sea) NPAL experimental data.

APPROACH

Coherence of low-frequency sound waves propagating over moderate and long ranges in the ocean diminishes due to sound scattering by internal waves (IWs), spice, and other ocean inhomogeneities. Studies of temporal coherence, horizontal and vertical coherence functions, and other statistical characteristics of acoustic signals propagating through a fluctuating ocean are important for many practical applications. With the ONR support, we have been developing a new, 3D, modal theory of

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low-frequency, long-range sound propagation through a fluctuating ocean which is applicable for both CW and transient acoustic signals. The results obtained so far have been summarized in four peer-reviewed publications in JASA [1-3,13] and presented at six international and domestic conferences [4-8,14]. Based on the 3D modal theory, the following statistical characteristics were calculated and analyzed: temporal coherence, horizontal and vertical coherence functions, mean sound intensity, cross-mode coherences, and mean sound field. The theoretical results obtained were compared with experimental data obtained in the North Pacific Acoustic Laboratory (NPAL) experiments carried out in the North Pacific in 1998-1999 [9] and in 2004 [10].

Dr. A. Voronovich and Dr. V. Ostashev are PI and Co-PI in this project.

WORK COMPLETED

During the reporting period, the following three tasks were completed:

Task 1. Based on the latest formalism of the 3D modal theory, effective computer codes were developed for calculation of the statistical characteristics of acoustic signals.

Task 2. Temporal coherence of acoustic signals was calculated and analyzed for the 2009 NPAL long-timescale experiment in the Philippine Sea.

Task 3. Vertical coherence of acoustic signals was calculated and analyzed for the 2009 NPAL long-timescale experiment in the Philippine Sea.

RESULTS

The following results were obtained in FY2011:

Task 1.
The latest mathematical formalism of the 3D modal theory of sound propagation in a fluctuating ocean is outlined in Ref. [13]. Based on this theory, efficient computer codes were developed for calculation of the propagation constants ξ_n, acoustic mode profiles $u_n(z)$, and the matrix of cross-mode coherences I_{nm}. This was an important step since the previous codes did not allow handling of many acoustic modes due to the memory restrictions. (All modal theories are inherently computationally demanding.) The new codes use not only RAM but also a hard disk for storing some data and, thus, allow handling of many more acoustic modes and higher acoustic frequencies. The codes are written in Fortran 90. In the codes, the sound-speed fluctuations are due to linear IWs with the Garrett-Munk (GM) spectrum. The second-order statistical characteristics of acoustic signals (e.g., temporal coherence, vertical and horizontal coherence functions) are expressed in terms of ξ_n, $u_n(z)$, and I_{nm} with formulas presented in [13]. Calculation and visualization of these statistical characteristics are done with MatLab. The codes developed were used for studies of the range and frequency dependences of the coherence time of acoustic signals for the Munk canonical profiles of the sound speed $c(z)$ and Brent-Väisälä frequency $N(z)$. They were also employed for predictions of temporal and vertical coherences for the 2009 NPAL long-timescale experiment in the Philippine Sea [12]. The results obtained are briefly summarized below.

Task 2.

In the 2009 NPAL experiment in the Philippine Sea, the 225-325 Hz WRC source was located at depth of $z = -1050$ m and range $R = 192.8$ km from the DVLA. The magnitude of the predicted normalized temporal coherence function $\Gamma(\tau)/\Gamma(\tau = 0)$ is plotted in Fig. 1 versus the time lag τ for a narrow-band signal with the sound frequency $f = 275$ Hz. The depth of the observation point, $z_{ref} = -1050$ m, coincides

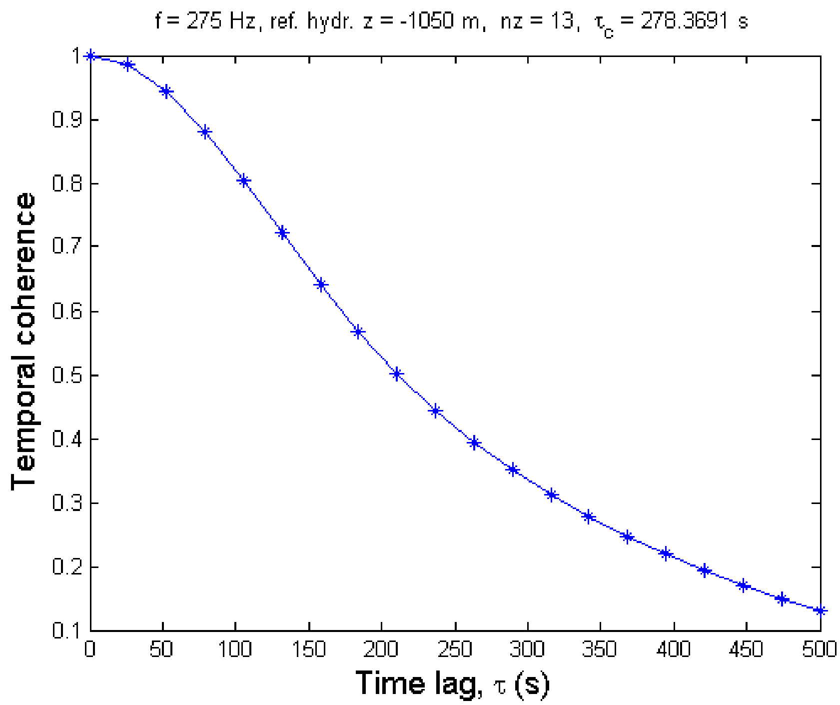

Figure 1. Predicted normalized temporal coherence function of a narrow-band acoustic signal versus the time lag for the 2009 NPAL long-timescale experiment in the Philippine Sea. The hydrophone depth is -1050 m, sound frequency f = 275 Hz, and propagation range R = 192.8 km.

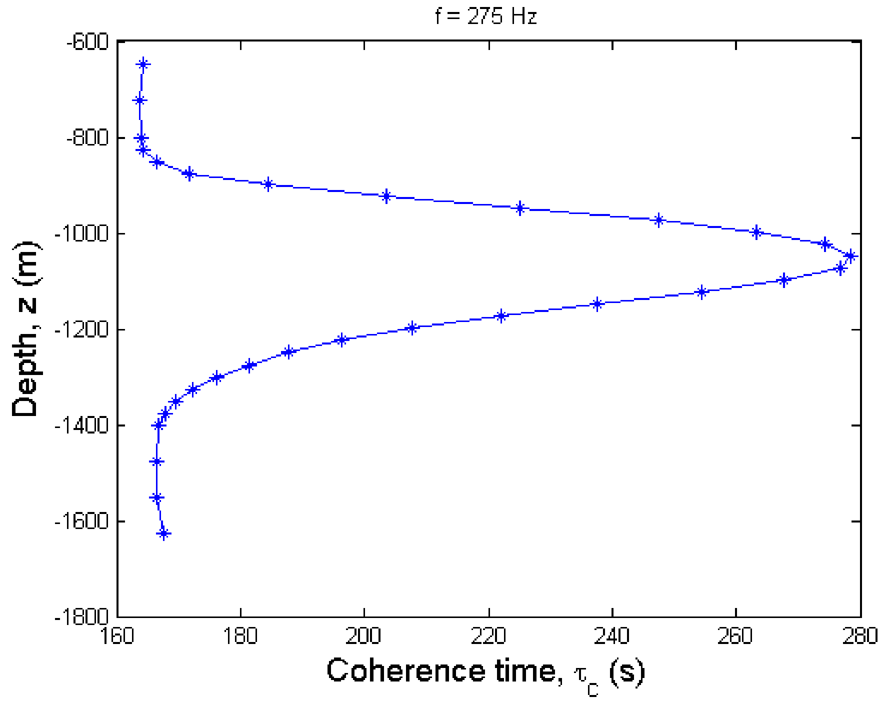

Figure 2. Predicted coherence time of a narrow-band acoustic signal versus the hydrophone depth z for the 2009 NPAL long-timescale experiment in the Philippine Sea. Sound frequency f = 275 Hz and propagation range R = 192.8 km.

with the depth of the sound-speed axis. In Fig. 1 and other figures below, the World Ocean Atlas was used to determine the annual averaged stratification of $c(z)$ and $N(z)$ for the DVLA location. It follows from Fig. 1 that the temporal coherence function $\Gamma(\tau)$ decreases with increasing time lag τ as it should. The coherence time τ_c is defined as a value of τ for which the temporal coherence function decreases by a factor $1/e$. In Fig. 1, the coherence time $\tau_c = 278.4$ s.

In Fig. 2, the coherence time τ_c is plotted versus the depths of hydrophones of the upper DVLA which were in range from -650 m to -1625 m. It follows from the figure that the coherence time varies from about 165 s to 280 s and has a maxim at the depth of the sound-speed axis, i.e., at $z = -1050$ m.

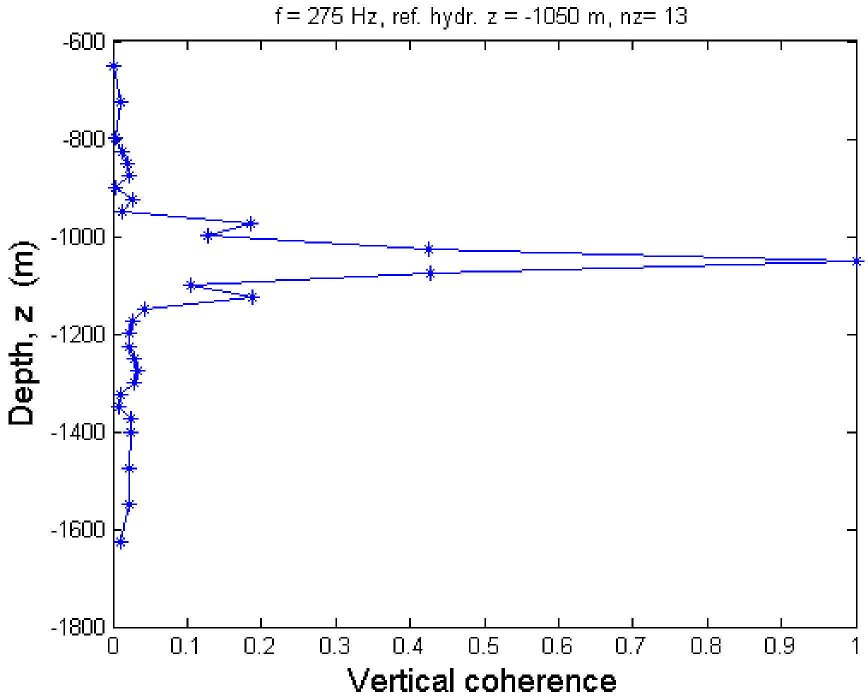

Figure 3. Predicted normalized vertical coherence of a narrow-band acoustic signal versus the hydrophone depth z for the 2009 NPAL long-timescale experiment in the Philippine Sea. The depth of the reference hydrophone is -1050 m, sound frequency f = 275 Hz, and propagation range R = 192.8km.

Task 3.

The vertical coherence of acoustic signals was also calculated for the 2009 NPAL long-timescale experiment in the Philippine Sea. In Fig. 3 the predicted normalized vertical coherence function $\Gamma(z-z_{ref})/\Gamma(0)$ is plotted versus the depths z of the hydrophones of the upper DVLA. The reference hydrophone is located at the depth of the sound-speed axis, $z_{ref} = -1050$ m. It follows from Fig. 3 that the vertical coherence generally decreases with increase of the vertical separation between two hydrophones. Note that this decrease is not monotonic: local maxima and minima are seen in the figure. This result is explained by the modal structure of the sound field in the ocean waveguide. The vertical coherence radius is about 30 m.

Figure 4 is similar to Fig. 3, but the depth of the reference hydrophone is $z_{ref} = -1325$ m. The vertical coherence radius is less than that in Fig. 3.

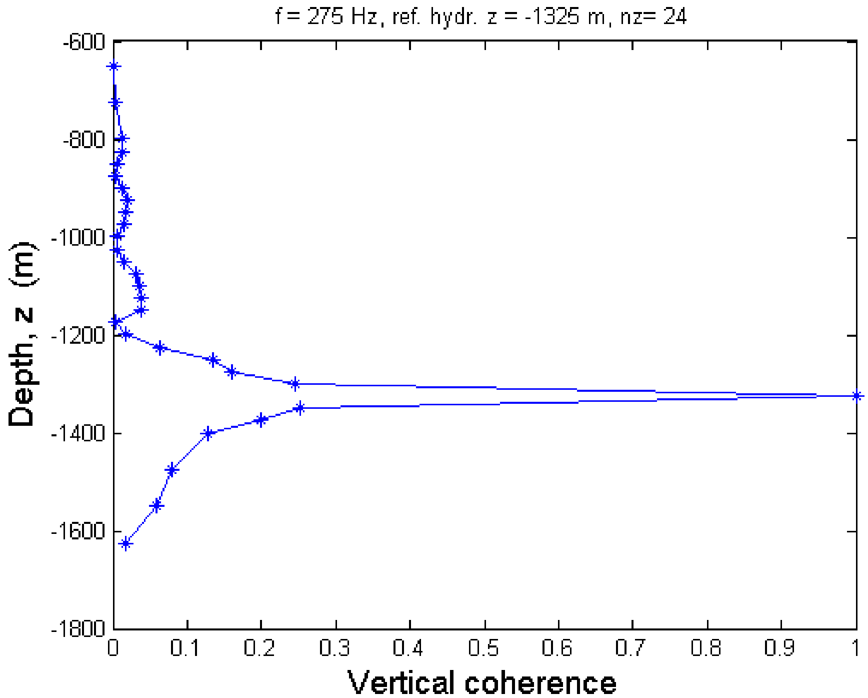

Figure 4. The same as in Fig. 3, but for the depth of the reference hydrophone z = -1325 m.

IMPACT/APPLICATIONS

New computer codes were developed for calculations of the statistical characteristics of acoustic signals in the 3D modal theory of sound propagation in a fluctuating ocean. The codes developed were applied to the analysis of range and frequency dependences of the coherence time of acoustic signals for the Munk canonical profiles of sound speed and Brunt-Väisälä frequency. They were also used for predictions of temporal and vertical coherences for the 2009 NPAL experiment in the Philippine Sea.

RELATED PROEJCTS

The 2009-2011 NPAL experiment in the Philippine Sea, see Ref. [11].

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