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14. ABSTRACT
The temporal coherence of long-range low-frequency signals at ocean-basin scales compares very well with predictions based on a model without tuning with data. We also provided evidence for a modern wave theory concerning where a medium influences signals between a source and receiver.

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acoustical coherence, ocean, internal waves, diffraction

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Final Report on ONR contract N00014-10-C-0480 titled “ Coherence of Sound using Navy Sonars.”

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This is the final report for ONR contract N00014-10-C-0480 titled “ Coherence of Sound using Navy Sonars.” The total cost of the program was $271,753.00, most of which is salary and indirect costs. The contract period began 13 May 2010, and will end at the end of May, 2012. The primary purpose of this contract was to see how well oceanographic models could predict the coherence of acoustic signals in space and time. Acoustic data came from Navy sonars.

The contract yielded three peer-reviewed publications and two publications that are under peer-review in scientific journals.

This contract involved four principal tasks. Each is discussed separately.

TASK I:
NUMERICAL COMPUTATIONS OF 2D & 3D SPATIAL SOLUTION OF ACOUSTIC WAVE EQUATION WITH INTERNAL WAVE FIELD

Three spatially-dimensional (3D) solutions to the acoustic wave equation are computationally intensive. The question we addressed is whether a 3D solution is needed to accurately model the spatial correlation of low frequency sounds at ocean-basin scales in the presence of a fluctuating field of internal waves. Theoretical approaches to this problem have been made, but do not appear to be valid at distances greater than 1000 km nor have they been evaluated with computers at such distances (Voronivich and Ostashev, 2006; 2007). We explored distances up to 4000 km and frequencies up to 250 Hz.

Our approach uses a 3D parabolic approximation of the linear acoustic wave equation. The sound speed field is taken to vary with depth and geographic location from a climatological background with fine-structure derived from internal waves. The time evolution of the internal waves is taken to follow the linear dispersion relation. The spectra of the field follows that given by Garret and Munk. The modeled acoustic field was computed between a point source and a set of horizontal arrays at distances from 500 to 4000 km. The supercomputer yielded hundreds of statistically independent realizations of the acoustic field at these arrays, requiring hundreds of thousands of CPU hours at the Navoceano supercomputer center. The 3D solutions were compared with 2D solutions based on uncoupled vertical slices through the 3D fields of sound speed.

We found that the horizontal correlation of the CW acoustic field was statistically the same with 2D and 3D solutions of the wave equation at 250 Hz and lower and up to 4000 km. Two papers provide these results. The first was published in the J. of Computational Acoustics, and the reference is

Spiesberger, J., Comparison of two and three spatial dimensional solutions of a parabolic approximation of the wave equation at ocean-basin scales in the presence of internal waves: 100-150 Hz, **18**, 117-129, 2010. The second paper is under review in the same journal.

TASK II:
MODEL/DATA COMPARISON OF TEMPORAL COHERENCE

The purpose of this research is to see if the temporal coherence of sound can be accurately modeled without tuning with data. We investigated two sections from the 1980s. The signal was emitted from the Kaneohe source (183 dB, 16 Hz bandwidth). Temporal coherence was analyzed at two Navy receivers at distances of 1400 and 3700 km. All the instruments sit on the sea-bottom with time bases governed by atomic clocks. Temporal evolution of sound was modeled using a 2D acoustic wave equation with sound speed obtained from climatology with superimposed fluctuations from internal waves. The linear dispersion relation was used to evolve fluctuations from internal waves.

We found the probability distribution function of temporal coherence was almost the same as predicted with the model. In both cases, the correlation time scale was between 5 and 10 min. We were surprised that the signal at 3700 km could sometimes be coherently integrated up to a day or more while slowly gaining signal-to-noise ratio.

Predicting the coherence time of sound by any means has been one of the most important problems in underwater sound since WWII. Based on our two studies and four previous ones, it appears that internal waves are primarily all that are needed to explain the bulk of our observations. To date, there is no reliable theory for coherence time. Our results could be useful for improving theoretical approaches. The ability to reliably predict coherence time may have applications for surveillance and wireless underwater acoustic communication systems.

The two papers that came out of this contract are:

Spiesberger, J.L., Internal waves' role in determining probability distribution of coherent integration time near 133 Hz and 3709 km in North Pacific Ocean, IEEE Ocean. Eng. **36**, 760-771 (2011).

Spiesberger, J.L., Internal waves' role in determining probability distribution of coherent integration time near 133 Hz and 1346 km in the Pacific Ocean, submitted to

J. Acoust. Soc. Am. (2012).

TASK III: MODEL/DATA COMPARISON OF SPATIAL COHERENCE

We measured the spatial correlation of a broadband impulsive acoustic signal at a Navy array. Comparison was made with a model. The model computed broad-band impulse responses at each hydrophone element. The model solved a 2-D parabolic approximation of the linear wave equation with sound speed coming from a climatological background and a 3D spatially and temporally varying sound speed field based on the linear dispersion relation for internal waves. Measured correlation was completely different than predicted from the model. We used several geoacoustic data bases for the acoustic properties of the sub-bottom, all without success.

The principal conclusion is that a 2-D model is likely not sufficient to understand the acoustic propagation in this case. The data are in shallow water, and the models show considerable interaction of sound with the bottom.

The disagreement between model and data opened what may be a new research direction where simple physical models might be used to understand the qualitative character of the data. Thereafter, 3D numerical models could be used to confirm the simple physical models. The research has direct application to surveillance systems.

TASK IV: REGIONS OF INFLUENCE AND MICROSCOPIC CHANGE IN ACOUSTIC TRAVEL TIME

In the 1980's, we measured very small changes in acoustic travel time between the Kaneohe source and several Navy sonars mounted on the bottom. The changes were about 10 ms, and had periods less than about 40 hours. Looking carefully at the impulse response with time, we found the early arriving acoustic paths changed travel time in near lock-step with late arriving paths, even though the early and late paths were separated in time by 4 s. This could not be explained in the 1980s. The problem was that we, and perhaps almost everyone, believed that widely separated paths in time sampled statistically uncorrelated fluctuations of the ocean at small scales, such as those associated with internal and inertial waves.

We discovered that the observations could be explained with modern theories of wave propagation. Instead of thinking that sound sampled the ocean along thin ray paths, the modern theories show that temporally separated paths can sample the same small scales in the ocean. The regions in the ocean that influence the sound are very long and do not look like rays. These data may be one of the first confirmations of these modern theories.

The results were published as follows.

Spiesberger, J., Where the ocean influences the impulse response and its effect on synchronous changes of acoustic travel time, J. Acoust. Soc. Am., **130**, 3642-3650, (2011).

Thank you for considering this final report.

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