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**Sixteenth and Final Report on ONR contract
N00014-06-C-0031 titled “ Coherence of Sound using Navy
Sonars.”**

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September 28, 2009

This report summarizes progress made since the fifteenth progress report, and also provides a final report on contract N00014-06-C-0031.

1. PROGRESS SINCE 6 JUNE 2009

This section briefly summarizes the work done under this contract since 6 June 2009.

The Journal of Computational Acoustics accepted a manuscript for publication. It discusses whether it is necessary to consider horizontal gradients of sound speed in the presence of internal waves to obtain an accurate value for horizontal coherence. Calculations were made up to a distance of 4000 km and up to a frequency of 150 Hz. We found no evidence that horizontal gradients were important. Calculations were made using two and three spatial dimensional solutions of a parabolic approximation. Solutions from the two dimensional solutions looked the same as from the three dimensional ones. The two dimensional solutions were made along vertical slices through an internal wave field varying in three spatial dimensions. There is good reason to be happy about the validity of two-dimensional solutions since they are much faster to compute than three-spatial dimensional solutions. However, the paper finds significant discrepancies between theoretical and numerical predictions for the shape of horizontal correlation.

A software bug was found for these calculations early this summer, and after the manuscript was accepted for publication. After the bug was fixed, calculations were rerun on the supercomputer at Navocean. After several months of elapsed time and using 80,000 cpu hours, we found the results to be unchanged! There does not seem to currently be a way to get around a complete re-calculation without a theory that has independently been verified with a numerical simulation. I am unaware of such a theory. In any case, the editor waited until the calculations were redone, and now it is off to the publisher. The re-calculation took most of my supported time in the past few months. The other work done during this summer involved extending the calculations to 200 Hz. Some computations are complete, but results are not yet analyzed. We have proposed finishing these computations under a new ONR contract next year.

One benefit of re-running the jobs this summer was our modification of software for use with MPI. MPI allows software to run faster on multiple cpus. The jobs needed to run faster so computations would be completed before the end of this contract.

2. FINAL REPORT

There are two primary goals in this contract. The most important is to see if the temporal and spatial scales of coherence are statistically consistent with our models without tuning with data. The short answer is yes. We analyzed and/or published results from two new experiments (Sections B and E, Fig. 1). Both involved using Navy sonars to receive the data. Section B is a 3683 km transmission between the Kauai source (75 Hz, 0.03 s resolution) and a towed array. Section E is a 1659 km transmission (250 Hz, 0.02 s resolution) from the Hoke seamount source (Curt Collins and C.S. Chiu) to a different towed array. In both cases the probability distribution functions for coherence time look like those predicted from the model. The model uses a GM spectrum [1, 2] to compute perturbations of sound speed on top of a climatological background [3]. The model generated perturbations on the background by multiplying vertical displacements of the internal wave field by the potential sound speed derivative in the vertical direction. The acoustic field is computed through snapshots of sound speed along the section using Tappert's sound-speed insensitive parabolic approximation [4].

The other result is that measured spatial coherence from Section E was found to be statistically consistent with our models.

In the past, we found excellent agreement between model and data for coherence on sections A and C (Fig. 1). Results for Section D are inconclusive (Table I) because the data appear to have not been analyzed correctly [8]. The Monte-Carlo approach used in our models appears to yield very accurate predictions of coherence. Comparison with many more data should be done. In my experience, previous theories have rarely if ever been able to reliably predict coherence times without tuning with data. So it comes as some comfort to have any approach that works (so far).

SECTION	DISTANCE (km)	FREQUENCY (Hz)	PULSE RESOLUTION (s)	DATA-MODEL AGREE?
A	3115	75	0.03	YES
B	3683	75	0.03	YES
C	3709	133	0.06	YES
D	3250	75	0.03	INCONCLUSIVE
E	1659	250	0.02	YES

Table I. Summary of five experiments where a Monte-Carlo technique is used to see if modeled and measured coherence times of sound are consistent. Section letter refers to Fig. 1. Analysis of sections A, B, C, and E are from [5], [6], [7] and [9] respectively. Results from Section D are inconclusive because observations of coherence time may not quite be complete [8].

Under this contract, results from Sections B and E were published in the J. Acoust. Soc. of America [6, 9].

The secondary goal of this contract was to ascertain the necessity of accounting for horizontal gradients of sound speed when modeling horizontal correlation at frequencies up to 200 Hz and distances of 4000 km in the presence of internal gravity waves. Results up to 150 Hz are accepted for publication [10]. Fortunately, we found no evidence that it is necessary to use a three-dimensional solution of the parabolic approximation.

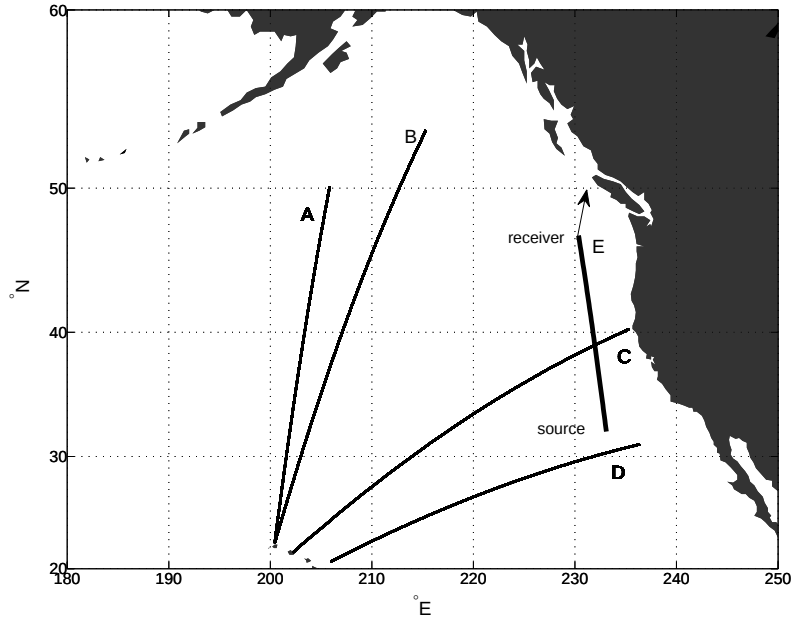


Figure 1: Five sections where blind predictions of coherence time have been made. A) 3115 km between a bottom-mounted source on Kauai (75 Hz, 0.03 s resolution) and a towed receiver, (B) 3683 km between the same source and a towed receiver, (C) 3709 km between a bottom mounted source at Kaneohe Bay, Oahu (133 Hz, 0.06 s resolution) to SOSUS station mounted on the bottom, (D) 3250 km transmission between source dangled from R/V Flip (75 Hz, 0.03 s resolution) and a vertical array, and (E) 1659.32 km transmission between a source moored over the Hoke seamount (250 Hz, 0.02 s resolution) and a towed array. Heading of the towed array is 12° True (arrow).

Solutions based on independent vertical slices through a three dimensional field are sufficient. We did find that theories yield inaccurate shapes for the horizontal correlation function.

OTHER DATA

We received data from a Navy test in the Atlantic in 2009. Data from arrays were sent to us for future analysis. The purpose is to analyze spatial coherence of sound over a wide range of frequencies. This MPI know-how gained this summer (Section 1) will be needed to model the horizontal coherence of sound for these data in the future.

The biggest disappointment of this contract was our inability to detect signals from the Kauai source at a towed array to the East of Japan. Data from the array were provided by the Navy. It appears the signal was blocked by seamounts. In my experience, this was the first time that signals were not collected from Navy Sonars.

The flip side is much brighter. We demonstrated that Navy sonars are important for collecting data that contribute to scientific progress at no additional cost to existing programs at the ONR.

EXPLAINING ONE SECOND BIAS WITH HYCOM MODEL

We proposed using the HYCOM model to explain late-arriving energy observed in several experiments. The late-arriving energy cannot be explained with sound speed based on a climatological background, nor with the addition of sound speed fluctuations from internal waves. We hypothesized that late-arriving energy, sometimes lasting a second, is due to the mesoscale which is not part of our current models. The HYCOM oceanographic models include the mesoscale. We accessed the HYCOM models, and converted those outputs to sections of sound speed corresponding to some of our data sets from the past. We found, however, that the HYCOM models were not accurate enough to replicate the basic impulse response even before the late-arriving energy. In other words, climatological data via Levitus's database are more reliable than HYCOM in those applications. We discussed the situation with Dr. Harley Hurlburt who identified the problem with the HYCOM models. The models used an incompressibility assumption that yielded incorrect pressures at depth. He did not believe a simple correction was possible. Unfortunately, the acoustic impulse response is sensitive to this modeling error. Newer versions of the models do not make this approximation regarding incompressibility. So we may return to the HYCOM models in the future, particularly when analyzing new data from the Atlantic.

Thank you for considering this final report.

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