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14. ABSTRACT This research intended to demonstrate that the two-point acoustic time domain Green's function (TDGF) could be obtained in the ocean using natural surface noise. The potential feasibility of the proposed research was suggested by our preliminary work using shipping noise which we briefly review here as a indication of the components necessary to conduct the research contained within the proposed effort.						
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# **FINAL REPORT FOR AWARD N00014-03-1-0478**

## **I: Extracting Coherent Structure From High Frequency Ocean Noise**

Hee-Chun Song, Philippe Roux, W. S. Hodgkiss, and W. A. Kuperman

Marine Physical Laboratory  
Scripps Institution of Oceanography  
La Jolla, CA 92093-0238

and

## **II: Expansion to Extracting Coherent Structure From High Frequency Ocean Noise W. A. Kuperman**

### **Objectives Proposed**

I: In this research effort, we will study, using theory and experiment, the space-time wavefront coherence properties of surface noise not previously explored. We seek the underlying physics and signal processing methods that will ultimately allow for the extraction of wavefronts representing the time-domain Green's function (TDGF) between noise observation points. An important potential use of the latter results is for inversion. The central effort of this research will be to develop the appropriate theoretical structure and subsequent processing tools and then to experimentally demonstrate this phenomenon with two sequenced experiments.

II: Under ONR grant N00014-03-1-0478, the Marine Physical Laboratory (MPL) is studying space-time wavefront coherence properties of surface noise. MPL will expand our work to cover the preparation and production of a conference program, a book of abstracts, conference proceedings and a special journal issue of refereed papers. The conference is an international conference on Underwater Acoustic Measurements: Technologies and Results, which will be held at Heraklion, Crete, Greece during the months of June and July 2005. Travel is requested to provide for a senior scientist to attend meeting and collaborate on the research in addition to providing funding for the conference program materials.

### **Background**

The continuous, very long-term, average correlation of ocean noise between sensors eliminates, by the very nature of the processing, any specific target location information. This processing should yield, though, a representation of a time averaged snapshot of the acoustical environment, independent of any specific sources. Hence, this method, in a sense, is a *passive* technique to measure transmission loss. The sources of ocean surface noise [1,2,3] (natural and manmade) as well as the subsequent average spatial distribution

of ocean noise [4,5] have been studied extensively. However, because the instantaneous distribution of all the mutually incoherent sources is extremely variable in space and time, robust, space-time observables of ocean noise are difficult to identify.

This proposed research effort was motivated by the ultrasonic research of Weaver and Lobkis [6,7] and our subsequent exploration into a similar concept using NPAL data of opportunity [8] when there were no source emissions [9]. Weaver and Lobkis have shown that the long-time, two-point correlation of random (Brownian motion) noise in an aluminum block cavity yields the (deterministic) time-domain Green's function between the two points. Our NPAL analysis retrieved an analogous result. However, the data was dominated and unnecessarily complicated by shipping noise. A higher frequency effort (i.e., sans shipping noise) would isolate all the relevant physics concerning extracting a deterministic Green's functions from ocean random noise. The necessary experimental component is time synchronized acoustic arrays. Such data was not available in the frequency regime of interest.

## Approach

We intended to demonstrate that the two-point acoustic time domain Green's function (TDGF) could be obtained in the ocean using natural surface noise. The potential feasibility of the proposed research was suggested by our preliminary work using shipping noise which we briefly review here as a indication of the components necessary to conduct the research contained within the proposed effort. In particular, the long-time correlation between a receiver and elements of a vertical array of receivers yields a wavefront arrival structure at the array that is identical to the structure of the TDGF except that the amplitudes of the individual wavefronts are shaded by the directionality of the noise sources. The Green's function emerges in both the cavity and ocean cases from those correlations such that *each noise emission passes through both receivers*. Since the Weaver result is for volume distributed sources in a multiscatter, cavity-like environment, the sources contributing to the construction of the TDGF are also distributed over three dimensions. However for the ocean environment considered here (there is no significant 3-dimensional multiscattering in the frequency regime of the available data), only surface sources aligned along the horizontal line between the receivers can contribute over a long-time correlation.

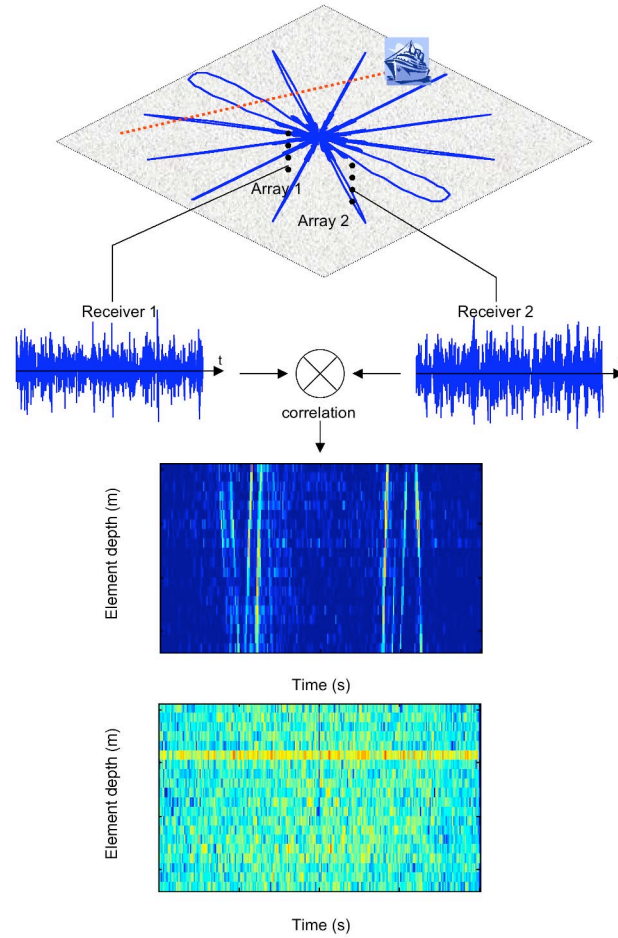


Figure 1.

The overall concept is summarized in Figure 1 in which noise at a receiver in array 1 is pair-wise cross-correlated with noise at individual receivers in array 2. This correlation is a function of delay time and vertical position (depths of receivers in array 2) as is the TDGF between a position in array 1 and the receivers of the array 2. The directionality of the correlation processing is schematically projected on the upper surface, the broadest lobe being along the axis between the two arrays. Sources off this axis will average down because of their different correlation times (determined by the projection of the horizontal propagation vector along the horizontal line between the receivers). The basic difference between the Weaver cavity configuration and ocean noise is the three-dimensional discrete modal physics of the cavity *vs* the ocean waveguide physics of standing waves in the vertical coupled to traveling waves in the horizontal direction. For the latter, this means that a ray with a vertical component can, if aligned along the receiver horizontal axis, pass through both receiver points by reflection or refraction; however, if the ray has a horizontal component not along the horizontal line between the receivers, it cannot be reflected back to the second receiver and therefore cannot contribute to building up the TDGF. This dimensional constraint does not apply to the cavity. Finally, in Figure 1 we show a schematic of the correlation process leading to

two displays. The first is a multi-day composite of three 20-minute correlation intervals of data discussed below and processes as described with data taken synchronously as described. The wavefronts in the display obtained from the correlation processing is the TDGF between a receiver at a particular depth in the array on the left and the array on the right. The arrival structure, consists of direct path, surface reflected, bottom reflected, etc. The second display is from correlating data that were taken at different times. The lack of structure is consistent with the hypothesis above requiring an accumulation of arrivals coming from the same individual sources and hence requiring the synchronicity between arrays. The downside and subsequent inadequacy of the data is that it is ship dominated. This allows for too many distortions in the data. These distortions are understandable but hinder us from reaching the asymptotically correct TDGF.

In analogy to the Weaver volume cavity noise, we would ideally like to consider only natural ocean surface noise sources that are typically uniformly distributed over the ocean surface which is the case as one goes to higher frequencies ( $> \text{kHz}$ , see [1]). However, to date, such data on synchronized vertical arrays in this high frequency regime are not available. For the lower frequency case ( $\sim 100 \text{ Hz}$ ), data is dominated by shipping noise, and while the concept remains the same, the relative amplitudes of the wavefronts that become observable will be dependent on the specific shipping distribution during the correlation time interval. The best data should display no specific events and is approximated well by the theory of uniformly distributed surface noise sources.

The actual measurement and signal processing that is to be done in the time domain where the correlation function  $C_{AB}(\tau)$  is measured using  $C_{AB}(\tau) = \int S_A(t) S_B(t + \tau) dt$ , where  $S_A(t)$  and  $S_B(t)$  are the ambient noise received on receivers A and B at time  $t$ . Note that the correlation processing requires data measurement that have a common clock time.

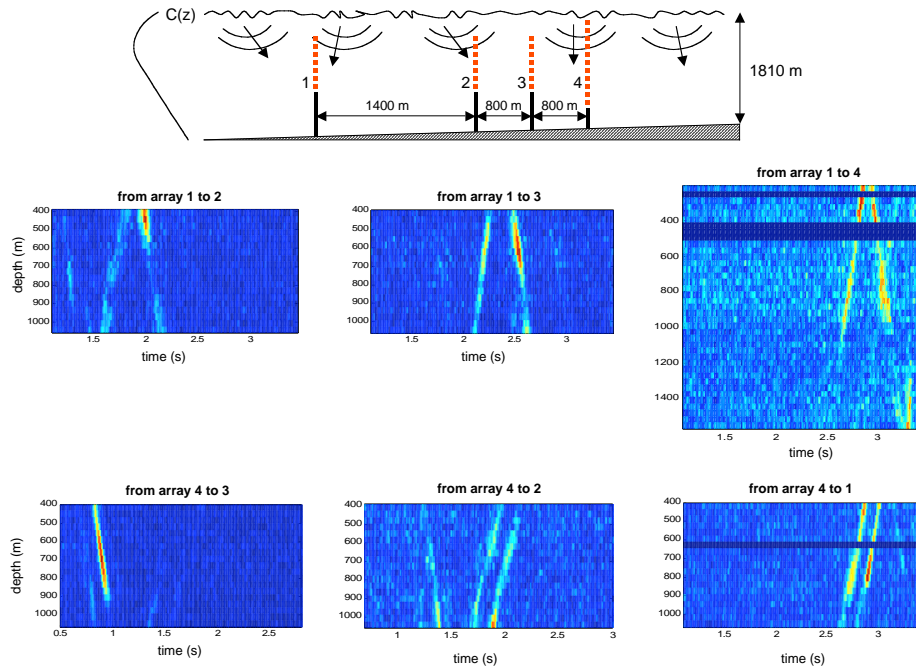


Figure 2.

We have used data of opportunity from the NPAL program originally taken for other purposes, but when the source was not emitting. There were actually four vertical arrays available from the NPAL experiment so that we could measure the evolution of the TDGF as a function of the travel time corresponding to the separation between, say, array 1 and arrays 2, 3 and 4 as shown in Figure 2. Note from the correlation lag times that we have extracted the same wavefront as it would propagate from a point source to distances of 2200 m, 3000 m and 3800 m, respectively. We also show that we recover the TDGF for the opposite direction by reversing the correlation process. Note that the sloping environment results in the asymmetry between the two directions, i.e., upslope increases the reflection angle.

We have demonstrated the feasibility through theory and data analysis that we can recover the time domain Green's function between two points in the ocean using measurements of ocean noise at the two respective points. In the NPAL data analysis, we have used the twenty minute data blocks that were available and it is not likely that we have done sufficient time averaging for the optimal result for a shipping dominated environment. Since shipping noise is dominant at lower frequencies ( $<1000$  Hz), we expect that high frequency will yield the most complete, uniformly converging, two-sided wavefronts predicted by theory. The required theoretical questions to be answered all revolve around the time scale necessary to build up the TDGF. This is a challenging broadband "self averaging" issue to which we have devoted a great deal of analysis.

## Results

I. Among the results, the theory of the buildup of the correlation function was developed. Results also yielded the non-intuitive results that random noise can be used to synchronize arrays (see Figure 3) and also perform array element localization.

A series of journal articles (see publications below) were published analyzing most aspects of the theory and data processing associated with using correlation extraction of signals from noise. There were also spinoff papers in applying the noise correlation method to seismology and physiology (also in publication list).

II. The effort in support of the Crete 2005 Conference was completed.

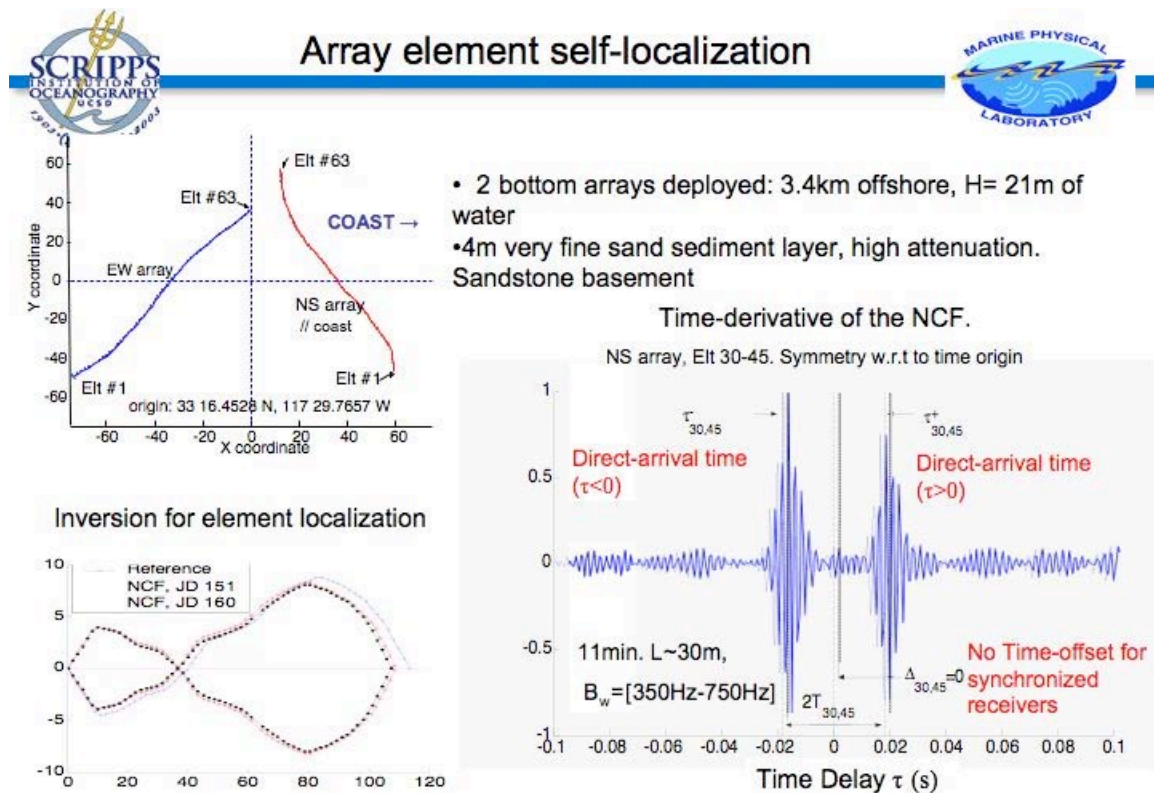


Figure 3.



## **Publications from the Supported Research**

Roux, P., K. G. Sabra, W. A. Kuperman, A. Roux  
Ambient noise correlation in free space: theoretical approach  
**J. Acoust. Soc. Am.**, **117(1):79-84 (2005).**

Roux, P., W. A. Kuperman  
Time reversal of ocean noise  
**J. Acoust. Soc. Am.** **117(1):131-136 (2005).**

Sabra, K. G., P. Roux, W. A. Kuperman  
Arrival structure of the time-averaged ambient noise cross-correlation function in an oceanic waveguide  
**J. Acoust. Soc. Am.**, **117(1):164-174 (2005).**

Sabra, K. G., P. Roux, A. M. Thode, G. L. D'Spain, W. H. Hodgkiss, W. A. Kuperman  
Using ocean ambient noise for array self-localization and self-synchronization  
**IEEE J. Oceanic Engr.** **30(2):338-347 (2005).**

Sabra, K. G., P. Gerstoft, P. Roux, W. A. Kuperman, M. Fehler  
Surface wave tomography from seismic ambient noise in Southern California  
**Geophys. Res Lett**, **32**, doi:10.1029-2005GL023155 (2005).

Roux, P., K. G. Sabra, P. Gerstoft, W. A. Kuperman, M. Fehler  
P-waves from cross-correlation of seismic noise  
**Geophys. Res Lett**, **32**, doi:10.1029/2005GL023803 (2005).

Sabra, K. G., P. Roux, W. A. Kuperman  
Emergence rate of the time-domain Green's function from the ambient noise cross-correlation function  
**J. Acoust. Soc. Am.**, **118:3524-3531 (2005).**

Sabra, K. G., P. Roux, P. Gerstoft, W. A. Kuperman, M. Fehler  
Extracting coherent coda arrivals from cross-correlations of long period seismic waves during the Mount St. Helens 2004 eruption  
**Geophys. Res. Lett.** **33**, L06313, doi:10.1029/2005GL025563 (2006).

Gerstoft, P., K. G. Sabra, P. Roux, W. A. Kuperman, M. Fehler  
Green's functions and surface wave tomography from microseisms in Southern California  
**Geophys.** **71(4)**, S123-131 (2006).

Sabra, K. G., S. Conti, P. Roux, W. A. Kuperman  
Passive in vivo elastography from skeletal muscle noise  
**Appl. Phys. Lett.**, **90**, 194101 (2007).

## References

1. G. M. Wenz, *J. Acoust. Soc. Am.*, **34**, 1936-1956 (1962).
2. Wenz's results have been compared against more recent data in R. K. Andrew, B. M. Howe, J. M. Mercer and M. Dzieciuch, *J. Acoust. Soc. Am* **112**, 2260(2002)
3. R. J. Urick. *Ambient Noise in the Sea*. Peniinsula Publishing, Los Altos (1986).
4. D. Ross. *Mechanics of Underwater Noise*. Peniinsula Publishing, Los Altos (1987). Estimates of shipping densities given extrapolate to a distribution with more than 1 ship per square degree which suggests (and has been confirmed for many years in the field of Underwater Acoustics) that except for nearby specific ship tracks, distant shipping can be considered to be smeared out over the large surface of the ocean, albeit with a directional dependence.
5. W. A. Kuperman and F. Ingenito, *J. Acoust. Soc. Am.*, **67**, 1988-1996 (1980).
6. R. L. Weaver and O. J. Lobkis, *Phys. Rev. Lett.* **87**, 134301 (2001).
7. O. I. Lobkis and R. L. Weaver, *J. Acoust. Soc. Am.*, **110**, 3011-3017 (2001)
8. The North Pacific Acoustic Laboratory (NPAL ) experiments were designed to study coherence of acoustic signal propagating long distances in the ocean. The acoustic source was 3000 km from the arrays. The NPAL group (J. A. Colosi, B. D. Cornuelle, B. D. Dushaw, M. A. Dzieciuch, B. M. Howe, J. A. Mercer, R. C. Spindel and P. F. Worcester) provided us with noise data from their receiver array during times when their source was not transmitting. Their array technology is the same used in the Acoustic Thermometry of the Ocean experiments: ATOC Consortium, *Science* **281**, 1327-1332 (1998).
9. P. Roux, W. A. Kuperman, et. al., "Coherent wavefronts from ocean noise," (in preparation, January 2003).