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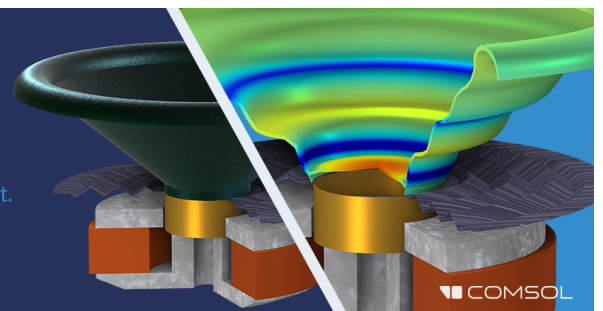
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# Extracting the local Green's function on a horizontal array from ambient ocean noise

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**Abstract:** Using only ocean ambient noise recordings it is possible to approximate the local time domain Green's function (TDGF) and extract the time delays associated with different ray path between the elements of a bottom hydrophone array. Comparing the strength of the noise correlation function taken over increasing time windows with residual fluctuations points to an optimum time window to use in the noise correlation function. Through comparison with computer simulations the resulting time series is shown to accurately approximate noise responses in the environment. Analysis of the TDGF gives accurate environmental detail, specifically the critical angle at the water-sediment interface.

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## 1. Introduction

There has been significant work recently in extracting coherent signals from random noise data. Early work successfully extracted the time domain Green's function (TDGF) from an aluminum cube by correlating the Brownian noise recorded at sensors on two faces of the cube.<sup>1</sup> The same theory of correlating the random signals to extract their coherent aspects has been applied theoretically and experimentally to both land seismic and ocean environments. For land environments, seismograms were passively obtained in the stationary environments that accurately reflected active seismic results.<sup>2,3</sup> The noise correlation processing of ambient ocean noise has been shown to successfully extract coherent propagating wavefronts between hydrophone arrays<sup>4</sup> though correlation times are limited due to the dynamic medium. Practical applications of this technique include using a vertical array suspended from a towed buoy to create a passive fathometer<sup>5</sup> and array element localization of hydrophone receivers in a horizontal array.<sup>6</sup>

This paper will illustrate that it is possible to passively extract the local TDGF from ambient ocean noise recording taken along a bottom-mounted horizontal array where each receiver is turned into a virtual source. An ideal window of processing time is determined which allows for the maximum average signal correlation strength over the distance of the array. The resulting time series is shown to be consistent with previous active acoustic experiments of the region, and allows us to extract individual environmental details. This is illustrated by identifying the critical angle at the water-sediment interface.

## 2. Theory

The time derivative of the noise correlation function (NCF) has been proved both theoretically and experimentally<sup>4,7,8</sup> to be approximately the sum of the TDGF and the time-reversed TDGF between the two hydrophones<sup>8</sup>

$$\frac{d\langle C_{a,b}(\tau) \rangle}{d\tau} \approx -G(\vec{r}_a, \vec{r}_b; \tau) + G(\vec{r}_b, \vec{r}_a; -\tau),$$

where  $C$  is the cross correlation of the time-aligned signal between receivers  $a$  and  $b$  located at  $\vec{r}_a$  and  $\vec{r}_b$ , respectively, and  $\tau$  is the time delay between those two receivers. The cross correlation isolates and accumulates the time average of those source events in the environment which propagate through both hydrophones. The specifics of the length of time necessary for performing the cross correlation are dependent on the environment around the hydrophones and especially the distribution of noise sources.

The data used in the present analysis are the same data that were used for array element localization using the NCF technique.<sup>6</sup> In that analysis 11 min time averages of data were used to extract the coherent wavefronts between close (less than 28 m apart) hydrophone pairs. Here we have increased the length of time averaged in order to resolve the greatest distance between hydrophones (up to 115 m) on the array.

## 3. Experimental results

### 3.1 Data

The data used in this analysis were originally taken in May 1995, 3.4 km off the coast of southern California for the Adaptive Beach Monitoring experiment.<sup>9,10</sup> This work used the ambient noise data recordings from one of the two bottom mounted horizontal arrays located parallel to the shore in roughly 21 m of water. The environment around the hydrophone arrays was measured and modeled using active geoacoustic methods; two nearby conductivity, temperature, and density casts provided the sound speed profile for the water column. The measurements of the environment found this area to be essentially range independent. Each array of 64 hydrophones recorded almost continuously for 2.5 weeks at a sampling frequency of 1500 Hz. Throughout that time the hydrophones recorded significant biological activity, dominated by noise from the croaker fish (*Sciaenidae*) family.<sup>9</sup> The ambient noise levels were especially high at night as the fish migrated from the surf zone out to the area where the hydrophones were located. That the noise field was dominated by biological activity within the water column (as opposed to physical effects like waves breaking which localize sound at the surface) made this data set particularly useful for extracting the approximate TDGF. That is, because the noise sources were volumetric a more accurate representation of the amplitude of the time of arrivals can be expected versus having only surface noise sources.<sup>4</sup>

### 3.2 Results

Approximating the local Green's function using only the ambient noise recordings is limited by the characteristics of the noise that is recorded. Ideally the noise should be fairly isotropic, or at least spread throughout the area of the hydrophones. The recording should not contain individual loud events (such as source pings, motor noises, etc.) which may bias the correlation process. To that end, the noise recordings are filtered and smoothed (both the time series amplitude and in frequency spectrum) in order to minimize the influence of isolated unique loud events.

Deciding the length of time to use in the NCF is one of the challenges of this technique. To get the cleanest result the strength of the strongest arrival versus the residual fluctuations was tracked as successive additional successive 5 min samples were averaged into the correlation. The correlation of hydrophones with a greater distance between each other required a longer time correlation to produce a clear result. The changing ocean environment (and coastal pumps which turned on and off every few hours) meant using as short a continuous time

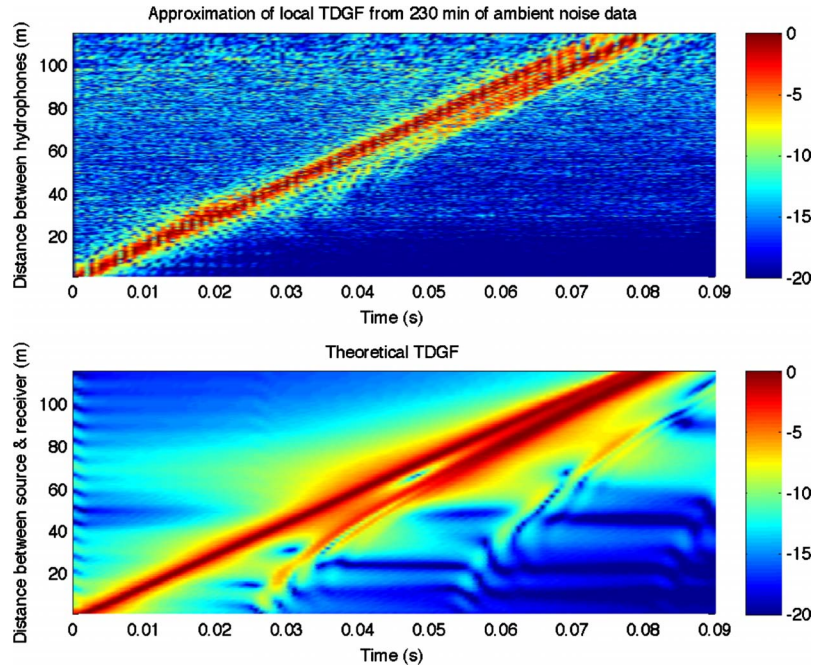


Fig. 1. (Color online) Comparison of the calculated and theoretical local TDGF shown in normalized dB. (a) Time averaged noise correlation function result: y axis is the distance between hydrophones, x axis is the correlation time. The location of the peaks show the propagation time of sound between the two hydrophones for the direct and surface reflected paths. (b) Spectral simulation of TDGF assuming a source and receiver at the given distance (along y axis) separation. Peaks show time of arrival (along x axis) of sound from theoretical source to receiver. Environment used for simulated Green's function is based on previous active acoustic inversions and measurements.

recording as possible. In order to minimize interference from pumps and coastal noise the data was filtered to the 250–750 Hz frequency band. Each 5 min segment of data was individually processed and then averaged until the strength of the strongest arrival found in the NCF compared with the residual fluctuations of the correlation function began to deteriorate. The cleanest result appeared to be a 3 h, 50 min window in the early morning hours. After this point there appears to be a change in the environment or the ambient noise such that averaging additional time began degrading the desired signal.

Since the environment was fairly homogeneous throughout the time of the recordings, different pairs of hydrophones with the same separation from each other give essentially the same response. The Green's function approximations for distinct pairs of hydrophones were then sorted by the distance between the pair of hydrophones. When stacked in order of increasing separation distance between hydrophones the NCF exhibits a time of arrival structure consistent with what would be expected from the theoretically calculated (using wavenumber integration techniques<sup>11</sup>) Green's function. Figure 1 shows the processed data stacked by separation distance between pairs of hydrophones and a simulation of the Green's function as though there were sources and receivers at the same positions along the array. The environment for the simulation is taken from the geoacoustic inversion of the same environment.<sup>10</sup> This comparison of the processed data with the simulated TDGF demonstrates that the processed data give an accurate time of arrival sequence for a signal traveling the given distance.

Clearly visible are multiple returns (most clear at greater distances) in the NCF of the data, which match the expected time of arrival of different ray paths between a source and receiver from the simulated Green's function. To verify this, a Monte Carlo noise simulation was made of a two dimensional noisy ocean environment model of the region around the hydrophone array. Discrete sound events were simulated randomly in time and range (up to 2 km)

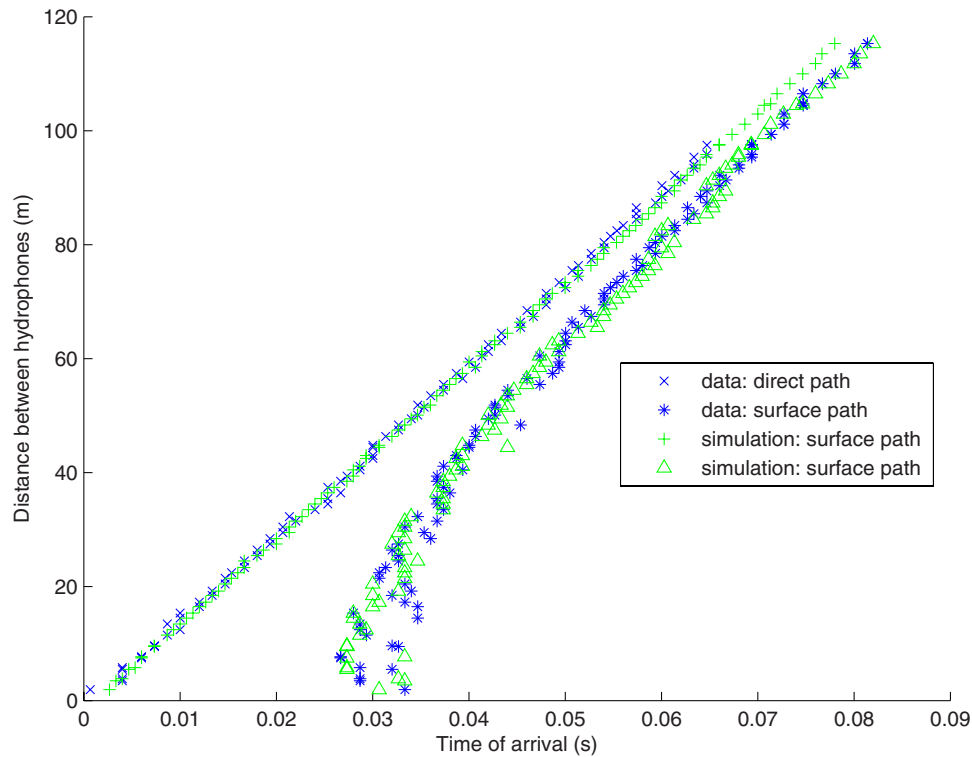


Fig. 2. (Color online) Comparison of peak time of arrivals ( $x$  axis) for direct and surface reflection paths for both the NCF processed data and the Monte Carlo noise simulation for increasing distance between hydrophone pairs ( $y$  axis). At smaller distances (less than around 60 m) the surface reflection does not tend to give a strong enough return to be accurately extracted. At greater distances the two paths approach each other enough that the stronger path can dominate. There are still two paths but at distances greater than approximately 100 m the surface path begins to dominate the data TDGF and it becomes difficult to isolate the peak arrival of the direct path arrival as it is overshadowed by the surface reflection return.

and located at depths within 2–3 m of the surface and bottom and theoretically propagated along the array. The noise was modeled in this way for computational efficiency and to better simulate the actual noise field which was primarily fish noise near the bottom and physical interactions along the surface. The resulting simulated time series was then NCF processed in exactly as the real data. Figure 2 shows the time of arrival of the peak strength for the direct and surface reflected ray paths for both the NCF processed data and the noise simulation. Both accurately extract the time of arrival for the direct and surface reflection paths, although the surface reflection path is most visible for shallower reflection angles (i.e., greater separation distance between hydrophones). At distances greater than 100 m, the surface reflection path begins to dominate over the direct path. At distances less than approximately 40 m, the strength of the surface reflection path return dissipates and a distinct second arrival becomes undetectable.

When isolated and plotted by distance the strengths of the surface path arrival by the theoretical reflection angle along the ocean bottom the resulting curve begins to approximate a curve for reflection coefficient. This is because of the greater attenuation of steeply reflected ray paths from sources far from the array.<sup>12</sup> Due to clipping and smoothing in the NCF processing though, it is only possible to isolate the relative strengths of the reflection at different angles of incidence and not the actual reflection coefficient. The strength of the surface reflection return was normalized by the distance the sound had traveled, and then normalized from zero to one.

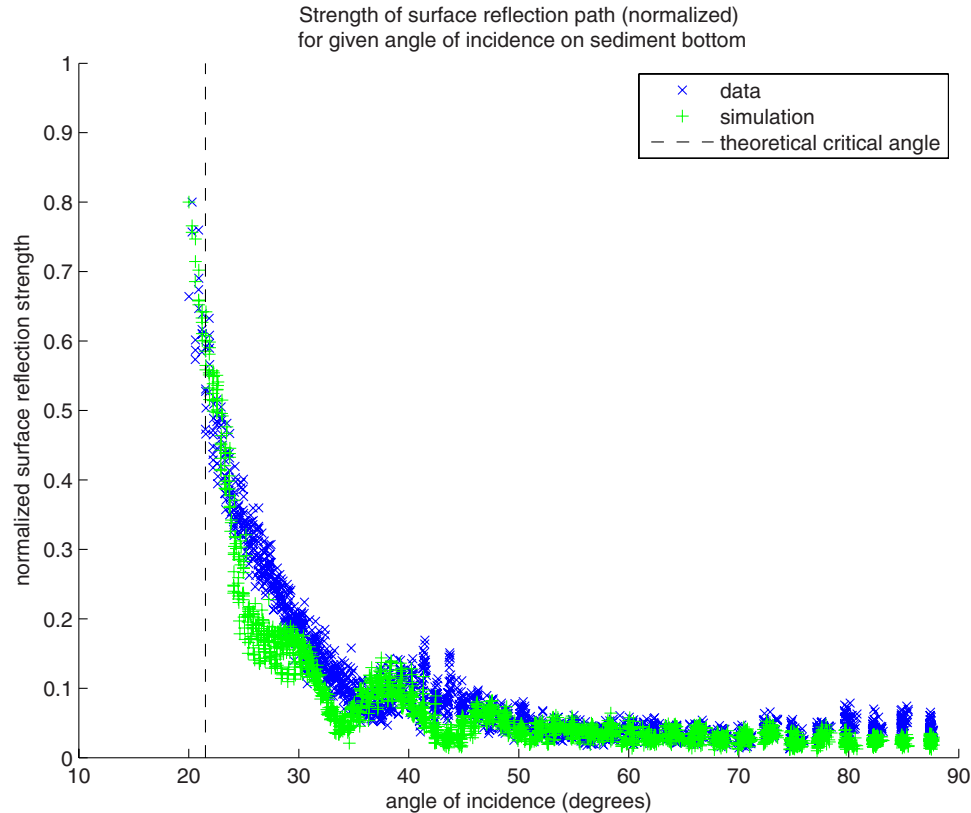


Fig. 3. (Color online) Strength of the surface reflection ray path return by theoretical angle of incidence on sediment floor ( $x$  axis) for both the processed data ( $x$ 's) and the noise simulation ( $+$ 's). The strength of the return was normalized by the surface reflection pathlength (to negate  $1/R$  spherical spreading term) and normalized from zero to one. Reflection strength curve indicates a critical angle of just over  $20^\circ$  which agrees with the theoretical critical angle (dotted black line) given the measured environment.

Figure 3 shows the normalized reflection strength for the NCF processed data and the Monte Carlo simulation. The resulting curve appears unfinished and is limited by the length of the array, but it points to a critical angle of incidence of around  $20^\circ$ .

This agrees with the expected critical angle from the previously calculated active geoacoustic inversions<sup>10</sup> of  $\theta_c = \cos^{-1} c_{\text{water}}/c_{\text{sediment}} = \cos^{-1} 1495 \text{ m/s}/1607 \pm 45 \text{ m/s} \approx 21.5 \pm 4^\circ$ . This value is shown on the figure with a dotted black line.

#### 4. Conclusion

Using only ambient noise on a horizontal array, a representation of the local TDGF was accurately extracted. By tracking the strength of the noise correlation function over time an optimum time to correlate can be chosen for a given noise environment. The resulting time series is shown to accurately approximate the local TDGF by comparison with simulations of the same environment. Analysis of the time series allowed us to accurately resolve environmental detail—in this case the critical angle for the ocean-sediment interface.

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