

**Passive estimation of the ocean seismoacoustic environment by extracting the Green's function from ambient noise.**

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**LONG TERM GOALS**

To develop the appropriate theoretical structure and subsequent processing tools and then to experimentally demonstrate utility of extracting the deterministic seismoacoustic properties of the oceanic environment from coherent processing of diffuse ocean ambient noise or scattered fields.

**OBJECTIVE**

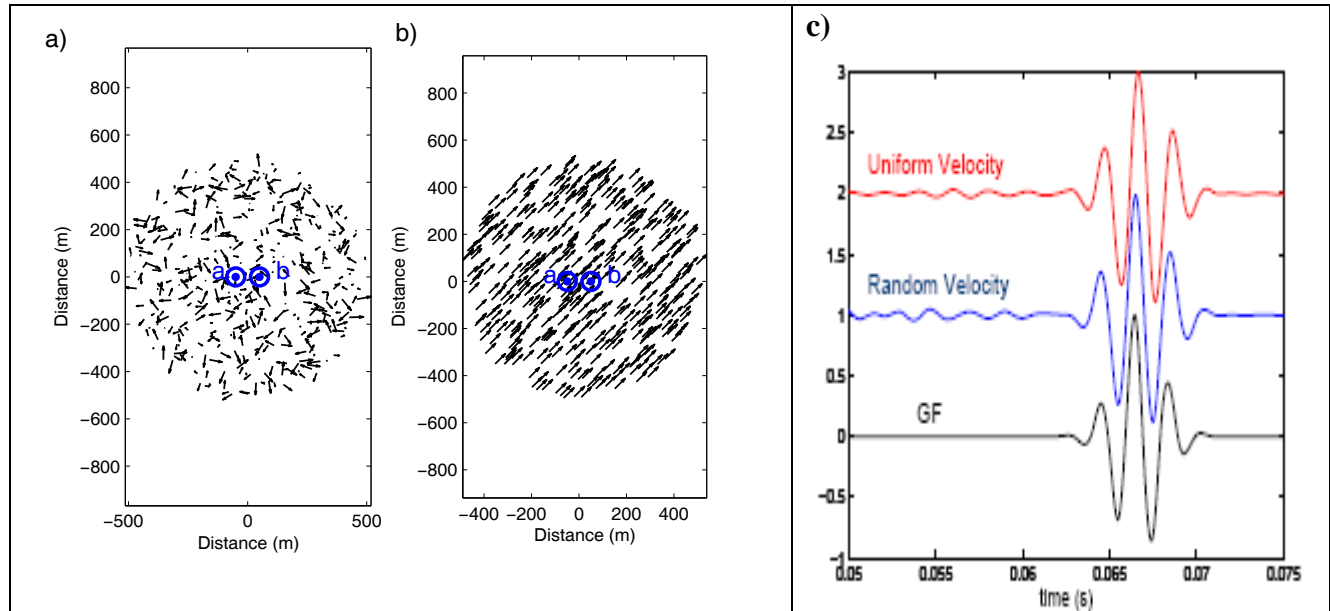
In the ocean, the dominant seismoacoustic noise source mechanism varies greatly across frequencies from ocean wave generated microseisms (0.05Hz-0.2Hz) to sea-surface noise (above 1kHz), including noise generated by human or biological activities. Though incoherent imaging with ocean ambient noise has been demonstrated (e.g. daylight imaging), a goal of this research is to use ambient noise, and even shipping noise, under certain conditions, to develop novel *coherent* imaging procedures such as tomography that typically require an active source or other noise based imaging methods in need of some coherence. Recent theoretical and experimental studies in ultrasonics, underwater acoustics and seismology have demonstrated that the time-domain Green's function (or impulse response)-TDGF- between two points can be obtained from the cross-correlation of ambient noise recorded at these two points [Fried et al., 2008]. These results provide a means for passive imaging using only the ambient noise field without the use of active sources. A potential scenario might include long-term deployment of ocean sensing systems requiring minimum power consumption, covert operations in hostile settings, or scenarios where active sources are limited by environmental regulations (e.g., Southern California).

**WORK COMPLETED**

**Influence of the noise sources motion on the estimated Green's functions from cross-correlations of ambient noise recordings between stationary receivers**

Previous theoretical studies of the performance of this noise-based passive imaging technique have assumed that the noise sources remain stationary. We have investigated the influence of the motion of the noise sources on this passive imaging technique theoretically first in free space, using a stationary phase approximation. The results were then extended to arbitrary environments using first order expansions of the recorded wave field. Although the Doppler

effect typically degrades the performance of standard wideband coherent processing schemes, such as time-delay beamforming for fast moving sources, it was found that the Green's function estimates extracted from ambient noise cross-correlations are not expected to be significantly affected by the Doppler effect, even when considering supersonic sources. Numerical monte-carlo simulations were conducted to confirm these theoretical predictions for both the case of subsonic and supersonic moving sources [Sabra, 2010].



**Fig 1.** Schematic of the sources and receivers geometry used for the two-dimensional numerical simulations. A reduced density of sources was used to enhance visualization. Quiver (vector) representation of the velocity vectors of the moving sources (a) Random distribution in orientation and magnitude. (b) Uniform distribution (i.e. constant orientation and magnitude). (c) Comparison of the actual stationary free-space Green's function (noted GF) between receivers a and b to the noise cross-correlation function computed either for a random distribution( see a) or a uniform distribution (see b) of the velocity vectors of the moving sources.

### A. Simulations of a random distribution of moving sources using a first-order formulation of the Doppler effect

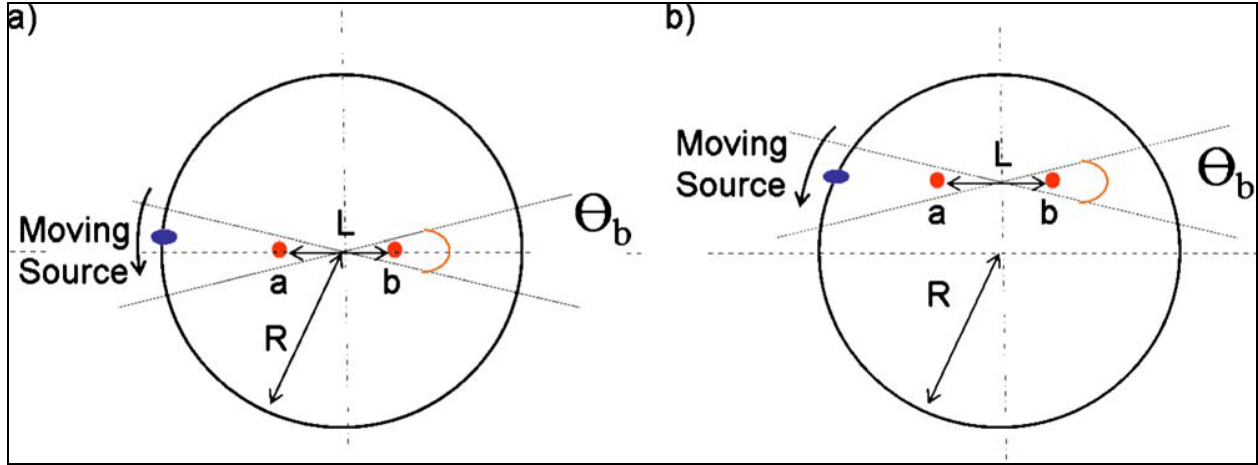
Free space simulations were conducted here. The sound speed  $c = 1500m/s$  and receiver separation distance  $L = 100m$  were selected to be representative of the top-view of an underwater acoustic experiment with a pair of hydrophones (noted a and b on Fig. 1). Furthermore, for simplicity, noise sources were assumed to be uncorrelated so that the contribution from each noise source to the total cross-correlation time function between the receivers could be added separately. The simulated short signals broadcast by each noise source were Gaussian-windowed sine pulses where  $fc = 500Hz$  is the center frequency of the pulse their effective bandwidth was  $B = [100Hz - 900HZ]$ . Noise sources were distributed (see Fig 1.a) up to an arbitrary distance of  $R < 500m$  away from the origin to account for the fact the contribution of the remote noise sources is in practice limited in range due to acoustic attenuation effects A high density was used for the noise sources surrounding the receivers with approximately one source every  $5m^2$ .

The average location for the sources was the same for Fig. 1.a and Fig. 1.b, only their velocity distribution actually vary. Two cases of sources motion were investigated numerically by using either 1) a random uniform distribution of the individual source velocity vectors  $\mathbf{v}_s$  both in orientation (i.e. over 360 degrees variations) and in magnitude ( $0 < |\mathbf{v}_s| < V$  for varying value of the upper bound  $V$  (m/s)) (see Fig. 1.a), or 2) a uniform distribution of the source velocity vectors pointing all at a 45 degrees orientation and having all the same magnitude  $|\mathbf{v}_s| = V$  (see Fig. 1.b). Fig. 1.a could be representative of an accumulation over time of randomly distributed wind-generated sea-surface acoustic events (e.g. white caps). The situation depicted in Fig 1.b may occur in the vicinity of the hydrophones if a prevalent wind or swell direction exists and uniformly advects the acoustically active white caps.

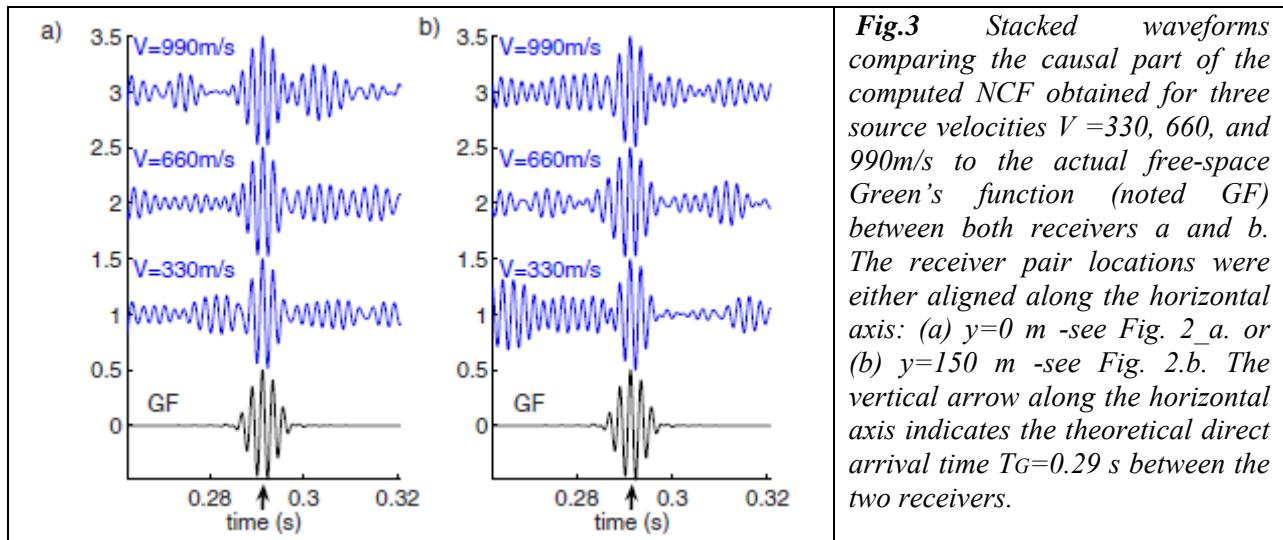
Fig. 1.c illustrates that the main coherent arrival of the computed noise cross-correlation time-function between both receivers provides a close estimate of the direct arrival time of the actual Green's function  $t_G = L/c = 66.6ms$  even for high value of magnitude  $V$  of the velocity vector, up to 50m/s, for both cases shown in Fig 1.a and Fig. 1b. Theoretical derivations are fully described in an upcoming publication [Sabra, 2009]

## **B. Direct simulation of a single noise source moving along a circular trajectory: Subsonic and supersonic cases**

The case of a broadband moving source, broadcasting a continuous signal (e.g., white noise) over long duration was also investigated. For simplicity, the case of a moving noise source having a circular trajectory at a constant angular velocity is considered here. The hypothetical case of a point source moving along a circular trajectory centered at the origin  $x=y=0$  with radius  $R=500$  m and with constant velocity magnitude  $V$  (see Fig. 2) was investigated here. The moving source is radiating continuously broadband white noise in the frequency band  $B=[300-600$  Hz] while rotating around the two receivers separated by a distance  $L=100$  m in air (sound speed  $c=343$  m/s). The sampling frequency was selected as 2 kHz, i.e., over three times the uppermost frequency, in order to satisfy the Nyquist criterion. Both subsonic and supersonic motions were considered with a Mach number  $M = V/c$  such that  $0.3 < M < 2.9$  (i.e.,  $100 \text{ m/s} < V < 990 \text{ m/s}$ ). Finally, two different geometries were selected for the receiver pair locations: either aligned along the horizontal axis  $y=0$  m (see Fig. 2.a) or  $y=150$  m (see Fig. 2.b). In the first case, the moving source has a zero radial while it crosses the line joining the two receivers (or endfire line) which thus minimizes, to the first order, the apparent Doppler shift at each receiver's location. On the other hand, the radial velocity is nonzero in the second case; thus both receivers will record a Doppler shifted version of the broadcast noise waveform.



**Fig.2** Schematic of the circular source trajectory and stationary receivers  $a$  and  $b$  aligned either along the horizontal axis: (a)  $y=0$  m or (b)  $y=150$  m.



**Fig.3** Stacked waveforms comparing the causal part of the computed NCF obtained for three source velocities  $V=330, 660,$  and  $990$  m/s to the actual free-space Green's function (noted GF) between both receivers  $a$  and  $b$ . The receiver pair locations were either aligned along the horizontal axis: (a)  $y=0$  m -see Fig. 2\_a. or (b)  $y=150$  m -see Fig. 2\_b. The vertical arrow along the horizontal axis indicates the theoretical direct arrival time  $T_G=0.29$  s between the two receivers.

Figure 3 shows, for a few selected values of the source velocity  $V$ , that the computed NCF have a main coherent arrival which coincides with the arrival of the free-space time domain Green's function between the two receivers for both selected source-receiver geometries (see Fig. 3). The vertical arrow on the time axis points to the theoretical arrival time  $T_G=0.29$  s in free space between both receivers, and appears to lie very close to the peak coherent arrival of the NCF computed for all values of  $M$ . This occurs since the relative Doppler shift between the two sensors is zero, to the first order, while the moving source crosses the line joining the two receivers and contributes to the coherent arrival of the NCF [Sabra, 2010]. Furthermore, the similarity of the NCF waveforms between the two selected receiver geometries, as shown on Figs. 3, confirms that the NCF is not sensitive to the absolute Doppler shift of the noise signals recorded by each receiver but only to their relative Doppler shift

**C. The main result of this study** is that the coherent arrivals of the ambient noise cross-correlation function are predicted not to be significantly modified by the noise sources motion, even for supersonic noise sources under certain conditions. Hence, these coherent

arrivals of the noise cross-correlation time function are expected to yield an accurate estimate of the *stationary* Green's function between the receivers, similarly to case of stationary noise sources as previously reported. The robustness to the Doppler effect of this noise cross-correlation process primarily results from its spatial directivity which emphasizes the contribution of the noise sources which cross the ray joining both receivers (i.e. the stationary phase regions). Indeed, when a moving noise source crosses those specific locations, the differential Doppler effect between the stationary receivers is minimal and thus resulting coherent time delay is not significantly affected by the Doppler effect

## **IMPACT**

It is conjectured that the results of this study could provide an upper bound to assess the performance of noise-based passive imaging in the presence of moving sources, especially at high-velocity. Hence, fast sources of opportunity (e.g. high-speed vessels, aircrafts) could potentially be used for noise-based tomography of the ocean seismo-acoustic environment when using a stationary network of passive sensors, without requiring additional Doppler corrections in data post-processing.

## **PUBLICATIONS**

1. K. G. Sabra, "Influence of the noise sources motion on the estimated Green's functions from cross-correlations of ambient noise recordings between stationary receivers," ,” *J. Acoust. Soc. Am.* , 127, 3577-3589 (2010).