Ocean Ambient Noise Studies for Shallow and Deep Water Environments

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LONG-TERM GOALS

The objective of this research is to study the ocean ambient noise field by means of new physics-based processing techniques, to determine ways to exploit noise for environmental characterization and to improve sonar-system performance.

OBJECTIVES

Effective operation of active and passive sonar systems relies on accurate modeling of sound propagation in the environment of the target and receiver. In shallow littoral water, propagation is affected by interaction with the acoustic waveguide boundaries, *i.e.* the sea surface and the seabed. The seabed reflection loss in particular is a primary contribution to the transmission loss, and is included in shallow-water propagation models as a power reflection loss coefficient, a function of frequency and grazing angle.

A simple passive technique for estimating the bottom loss by beamforming the ambient-noise field using a vertical line array has been developed by Harrison and Simons [Harrison, 2002]. The advantages of passive bottom-survey techniques include simpler measurement requirements, decreased risk of counter-detection, and minimal environmental impact.

Harrison and Simons' technique has so far been applied to data collected by moored or drifting arrays of lengths of the order of several to tens of meters. If this technique could be implemented using much shorter arrays, one could envision a cost-effective bottom-survey system composed by an array mounted on an Autonomous Underwater Vehicle (AUVs). Combining ambient-noise-based bottom survey with the versatility and simplicity of AUVs would result in a system capable of covering extended areas without requiring controlling surface vessels, complex equipment or human interaction during the mission.

The possibility of AUV deployment has made rigid, short arrays increasingly attractive, but their poor angular resolution represents a significant drawback for the purpose of bottom-loss estimation. However, beamforming has some inherent limitations, which affect in particular the angular resolution: All other array parameters being equal, the angular resolution improves when the array length

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increases [Johnson 1993]. The research described in this document focuses on estimating the reflection loss from the bottom by array processing of marine ambient noise, with a special focus on investigating and expanding the potential and capabilities of short arrays for this application.

Our recent efforts have focused on processing techniques that, by improving the performance of short arrays in reflection-loss estimation, can support the design of the AUV-based bottom-survey system described above. In recent work, we have proposed a new derivation in frequency-wavenumber domain of the power reflection coefficient from the array spatial coherence function [Publications #1 and #2]. Besides providing further theoretical support for Harrison and Simons' technique, whose original justification was based on an energy-flux argument, this also led to a processing technique that exploits the physical properties of the noise field to improve the angular resolution of the estimated reflection loss. The work has been finalized this year with a journal publication [Publication #3].

Furthermore, we have proposed and investigated a new technique for improving the reflection-loss estimation performance of very short arrays. We first studied its application in simulation and existing datasets. Later, our collaboration with the NATO-STO Centre for Maritime Research and Experimentation (CMRE, La Spezia, Italy) resulted in our participation to the REP14-MED measurement campaign (June 2014), during which ambient-noise data were collected both from a conventional vertical line array, and from an array designed as a prototype for a future AUV-mounted system. We then conducted the analysis of the application of the new technique to this original acoustic dataset.

APPROACH

A theoretical expression for the un-normalized spatial coherence function between two hydrophones in a vertical-line array is given by Harrison [Harrison, 1996]:

$$C_\omega(z) = \int_0^{\pi/2} \frac{2\pi \sin\theta_s \cos\theta_r}{1 - R_s(\theta_s) R(\theta_b) e^{-a s_c(\theta_r)}} \cdot \left\{ e^{i(\omega/c) z \sin\theta_r} e^{-a s_p} + R(\theta_b)\, e^{-i(\omega/c) z \sin\theta_r} e^{-a\,[s_c(\theta_r) - s_p(\theta_r)]} \right\} d\theta_r . \tag{1}$$

In Eq.(1), $C_\omega(z)$ is the coherence function for the hydrophone pair, assumed to be aligned with the z axis, with the first hydrophone at $z = 0$. Furthermore θ_r, θ_s, and θ_b are the ray angles at the receiver, the surface, and the bottom; s_c and s_p are the complete and partial ray-path lengths, whose dependence on θ_r is determined by the sound-speed profile in the water column; ω is the angular frequency; c is the sound speed at the receiver in the medium, and R and R_s are the bottom and surface power reflection coefficients. For the sake of simplicity, the dependence of the reflection coefficients on frequency is not indicated explicitly. Note that a is the power attenuation per unit length.

Although R depends on the frequency of the signal, one could make the often correct hypothesis that the amplitude terms in Eq. (1) are less important than the exponentials — in other words, although the reflection loss does depend (sometimes dramatically) on the frequency, we hypothesize that the spatial coherence function is essentially frequency independent. When this assumption is made, the dependence of the coherence function on the sensor spacing z lies primarily in the two exponentials, where z always appears multiplied by the angular frequency ω. This means that multiplying z by an integer factor (as is done to obtain the coherence function between different hydrophone pairs in the array) has the same effect as leaving z unaltered and multiplying ω by the same factor. The preceding statement can be exploited to extrapolate the coherence function measured by an M-element array: The maximum spacing for which the coherence function can be measured from data is $z=(M-1)d$, and the (extrapolated) value of the function at $z=nd\left(n\geq M\right)$ can be obtained by assuming:

$$C_{\omega}(nd)\approx C_{n\omega/(M-1)}\left[(M-1)d\right]. \tag{2}$$

This methodology (hereafter referred to as "Frequency-based array reconstruction", or FBR) is applicable as long as there are data available at the higher frequency required in Eq.(2), which depends on the sampling frequency and design of the acquisition system. The choice of the maximum spacing in Eq.(2) is made to maximize the sensor spacing that can be synthetically reconstructed with a given upper frequency limit.

WORK COMPLETED

A new technique (FBR) for improving the performance of very short arrays in reflection-loss estimation has been theorized. After a first confirmation from OASN [Schmidt, 2004] simulations of the validity of the assumption at the basis of FBR, the technique was applied to measured data from available acoustics datasets collected in the past by CMRE. Both Martin Siderius and Lanfranco Muzi participated in the REP-14 experiment and the techniques described were extended to the new REP14-MED dataset.

RESULTS

The bottom-loss estimates shown in this section are obtained by processing array data acquired during three separate experiments by the NATO-STO Centre for Maritime Research and Experimentation (CMRE — formerly NATO Undersea Research Centre).

TABLE I. Datasets and array basic features – all deployments were drifting, design frequency assumed at $c=1500\,\mathrm{m/s}$.

Dataset ID	Num. of elements	Spacing (m)	Sampling freq. (Hz)	Design freq. (Hz)
Boundary '03	32	0.50	6000	1500
Boundary '03	32	0.18	12000	4166
REP14-MED	32	0.18	50000	4166

In order to test FBR, first the reflection loss has been estimated by Harrison and Simons' technique using data from the full-length array. Then the procedure is repeated using only a subset of array elements, to see the effect of an array of reduced length on the estimated reflection loss. Finally, the data from the same subset of array elements is used to apply FBR, and the result is compared to the two previous estimates. The plots in Figure 1 show the results for data from the Boundary 2004 experiment. Note how the striations visible in the full-array result (due to the presence of layering in the bottom) lose a good amount of details when using only 20 of the available 32 elements. This effect is due to the lower angular resolution of the shorter array. Finally, note how FBR, by affording the reconstruction of the contribution to the spatial coherence function of the missing 12 sensors using only data from the same 20 sensors of the subarray (but over a wider frequency range), is capable of recovering most of the detail lost by the shorter array.

The same considerations can be applied to the plots in Figure 2, where the same procedure is applied to data from the Boundary 2003 experiment. The tighter spacing of the array makes it possible to estimate the reflection loss over a wider frequency range (up to the design frequency of 4166Hz). In this case, the relatively low sampling frequency does not allow FBR to reconstruct the reflection loss from the longer array up to the design frequency, but the available frequency range shows that the technique can still recover the detail lost by the shorter array.

Finally, Figure 3 shows the same procedure applied to data from the REP14-MED experiment. In this case, the subarray includes only 8 elements, so that its total length of 1.26m is close to that of an AUV-deployable array. The loss of detail in reflection loss, when Harrison and Simons' technique is applied to the subarray is dramatic. In this case the application of FBR is more "extreme" than before, as the attempt is made of quadrupling the length of the subarray, to reach the full length of the original 32-element array. Even so, the technique proves capable of recovering a great amount of detail by exploiting the full frequency range of the subarray data.

IMPACT/APPLICATIONS

This work may have a significant impact on several Navy sonar systems (e.g., ASW, MCM, underwater acoustic communications). Knowing the seabed properties will improve at-sea situational awareness by being able to accurately predict acoustic propagation. And, because this is a passive method it can be designed into a system used for covert activities, low power applications and can be used even in environmentally restricted areas.

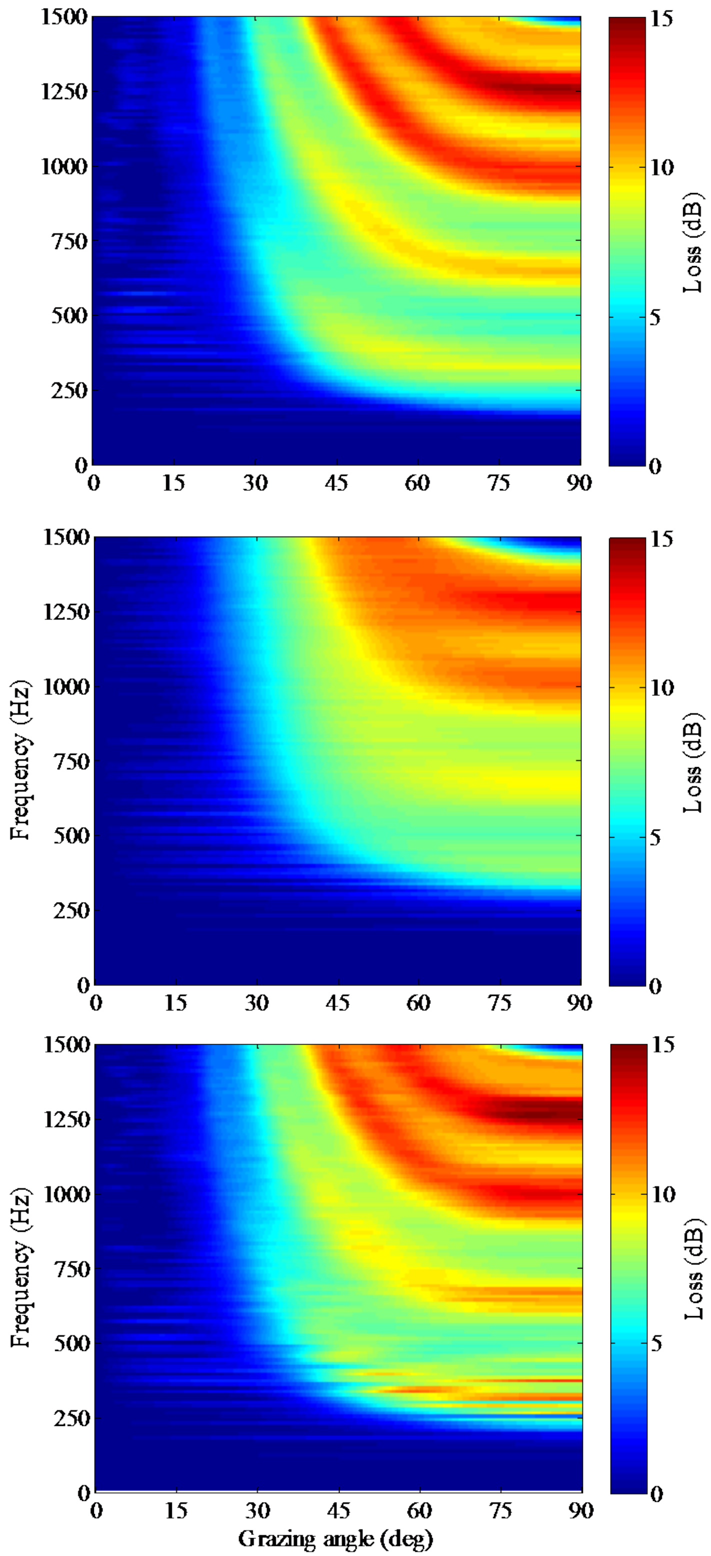

Figure 1: Data from the Boundary 2004 experiment: Reflection loss estimated using data from all the 32 array elements (top), and from only the first 20 elements by the conventional technique (center), and by reconstructing the 12 missing elements by FBR (bottom).

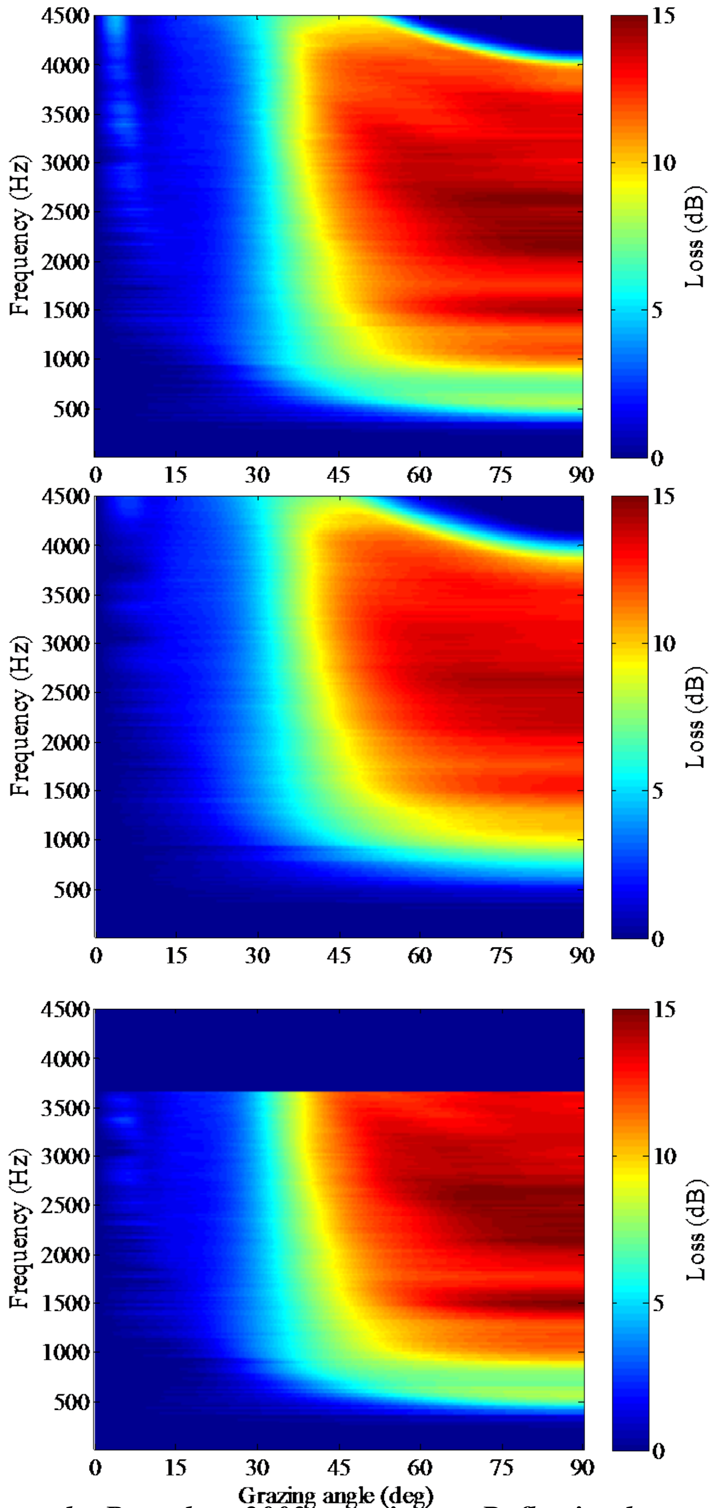

Figure 2: Data from the Boundary 2003 experiment: Reflection loss estimated using data from all the 32 array elements (top), and from only the first 20 elements by the conventional technique (center), and by reconstructing the 12 missing elements by FBR (bottom). Note that, in this case, the frequency range of available data does not allow to reach the array design frequency of 4166Hz in the reconstructed array.

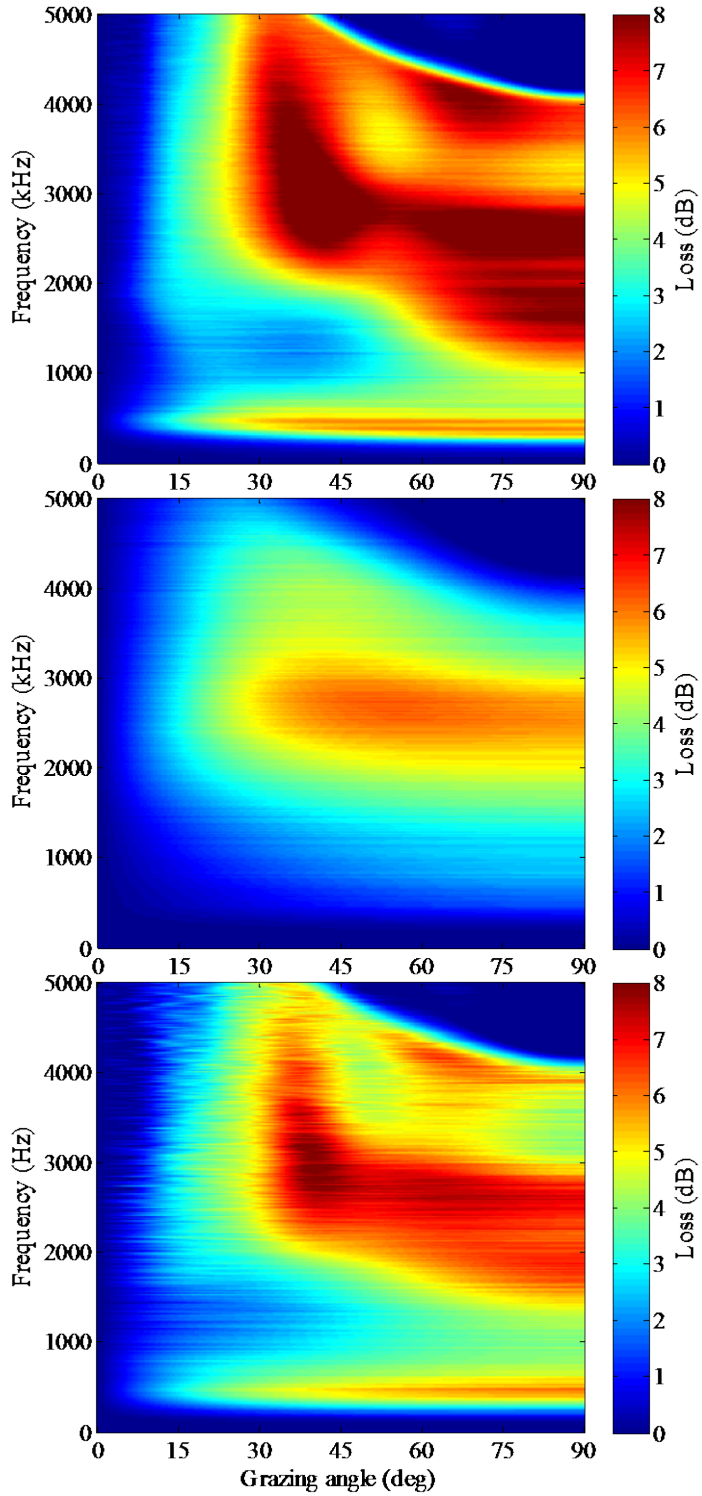

Figure 3: Data from the REP14-MED experiment: Reflection loss estimated using data from all the 32 array elements (top), and from only the first 8 elements by the conventional technique (center), and by reconstructing the 24 missing elements by FBR (bottom).

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