Impact of spatial aliasing on the use of coherent ambient noise processing for estimation of seabed layering

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ABSTRACT

Ocean acoustic noise can be processed efficiently to extract Greens function information between two receivers. By using noise array-processing techniques, it has been demonstrated that a passive array can be used as a fathometer [1]. Here, this approach is derived in both frequency and time domains and the output corresponds to the reflection sequence. From this reflection sequence, it is possible to extract seabed layering. In the ocean waveguide, most of the energy is horizontally propagating, whereas the bottom information is contained in the vertically propagating noise. Extracting the seabed information requires a dense array with sensor spacing comparable to the required resolution of the bottom layers. If velocity sensors are used instead of pressure sensors, the array spacing requirement can be relaxed.

I. SIMPLE EXAMPLE

A simple example motivates the approach and demonstrates that a vertical array can be used as a fathometer, see Fig. 1. Consider a simple 100-m deep ocean with a square pulse (width 0.1 s, amplitude 1) propagating down, reflected, and then propagating up (amplitude 0.5) and recorded on a 50-m long array with 20 receivers as shown in Fig. 1. The processing [1] calls for stacking the upgoing and downgoing signals, Fig. 1b and c. This is done by time delaying and summing at a reference depth, in this case (and all examples here) the ocean surface. Both stacked signals show a main peak, corresponding to the wave propagating with that speed, and a spread out waveform, corresponding to the signature obtained from stacking the opposite propagating wave. Finally, in Fig. 1d we crosscorrelate the up and down-going signals. This shows a triangular pulse of width 0.2 s appearing at a travel time corresponding to two water depths (2*100/1500=0.13 s). The triangular shape is due to the convolution of two square signals. In addition, there is some noise visible from time 0 to 0.067 s, due to the convolution of signals that did not propagate in the staking direction. The time extent of this noise corresponds to two times the travel time across the array length. The corresponding noise signal can be seen in Fig. 1b from 0.33–0.4 s. Within this interval, the level is fairly constant with small variations in amplitude. Though not visible in the plot, the shape at the peaks is a square wave with 19 peaks. The number of small peaks is proportional to the number of hydrophones in the array and depends also on the source waveform.

II. FREQUENCY DOMAIN

By beamforming, we can obtain the down- and up-going beams corresponding to downward and upgoing energy, respectively:

$$d_d(\omega) = \mathbf{w}_d^H \mathbf{p}; \qquad d_u(\omega) = \mathbf{w}_u^H \mathbf{p}$$

where $\mathbf{p}(\omega) = [\,p_1(\omega), p_2(\omega), \ldots\,]^T$. $\mathbf{w}_d$ and $\mathbf{w}_u$ are the steering vectors for down- and up-going energy, respectively. Cross correlating the two beams using conventional processing ($\mathbf{w}_u = \mathbf{w}$ and $\mathbf{w}_d = \mathbf{w}^*$):

$$C_{du} = d_d d_u^H = \mathbf{w}^T \mathbf{p}\mathbf{p}^H \mathbf{w}$$

This expression is very similar to the conventional beamformer $\mathbf{w}^H \mathbf{p}\mathbf{p}^H \mathbf{w}$ except that $\mathbf{w}^H$ is replaced with $\mathbf{w}^T$. Similar to classical beamforming there is a spatial aliasing, which requires the frequency to be less than the c/2d. For broadband methods and a single source, this requirement can usually be relaxed, as aliasing from several angles will average out the results. However, in the present application, the noise comes from all directions and these side lobes can destroy the response, as illustrated in Fig. 3.

III. SPATIAL ALIASING

It has been demonstrated that bottom properties could be extracted by comparing the upgoing and downgoing energy from a simple beamformer output [2]. The motivation for this approach is that upward propagating ambient noise has one more bottom bounce than downgoing ambient noise at the same angle. Note, that their processing is incoherent in the frequency domain whereas the present method is coherent.

An example of the frequency domain conventional beamformer output is shown in Fig. 2 based on the Mapex2kbis data [2]. Downgoing signals correspond to positive angles and upgoing to negative angles. A Kaiser-Bessel window was applied across phones. The covariance matrix has been normalized at each frequency by its trace, so that the energy for each frequency is the same (The unnomalized beam response can be seen in [2]). The antialiazing filter begins to roll off at 2 kHz. The nature of the beamformer output changes somewhat around 2.2 kHz, indicating that the compensation of the antialiasing filter has not been completely successful. The non-propagating electric noise can be seen at around 0 at frequencies greater than 2.2 kHz.

IV. EXPERIMENT

The data used to demonstrate the approach and its limitations are from the Mapex2kbis experiment on 22 November 2000 [2,3] where the vertical array was moored in 130-m deep water with the center of the array at 96 m depth. The site is a sandy bottom in the South Sicily area. The array was nested and two configurations with 32 phones and either 0.5-m spacing or 1-m spacing are used in the analysis. The experiment took place on the Malta Plateau. A seismic profile [3] (Fig 4) was obtained with the array moored 1 km further to the south. For reference, the envelope of the reflection sequence obtained at the array based on the observed ambient noise using high-resolution adaptive beamforming using (WNC-MVDR) is also shown.

REFERENCES

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[3] Fallat, M.R., P.L. Nielsen, S.E. Dosso, and M. Siderius, “Geoacoustic characterization of a range-dependent ocean environment using towed array data," *IEEE J. Oceanic Eng.,* 30, 198--206, doi: 10.1109/JOE.2004.838067 (2005).

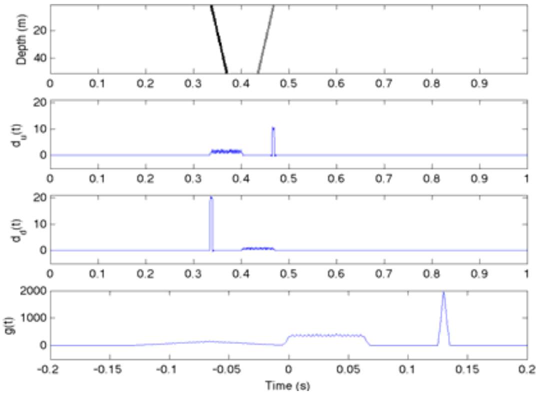

Fig. 1. Time domain processing of a simple arrival in a 100-m ocean with 20 receivers at 0--50 m depth. a) A square pulse 0.1-s wide with a downgoing component of amplitude 1 and an upgoing component with amplitude 0.5. b) Stacking the signal at the surface in upgoing direction. c) Stacking the signal at the surface in downgoing direction. d) Crosscorrelation of the stacked up- and down-going signals.

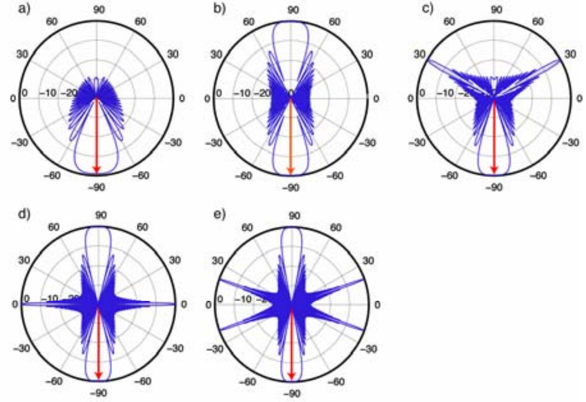

Fig. 3. Beam pattern for the downward beam (-90°) at a) 1 kHz, b) 1.5 kHz, c) 2 kHz, d) 3 kHz, e) 4.5 kHz. The first three frequencies used are indicated with Δ in Fig. 3. Grating lobes can be seen in b) at +90° c) at +30°, d) +90°, $0° e) +90°, ±20°.

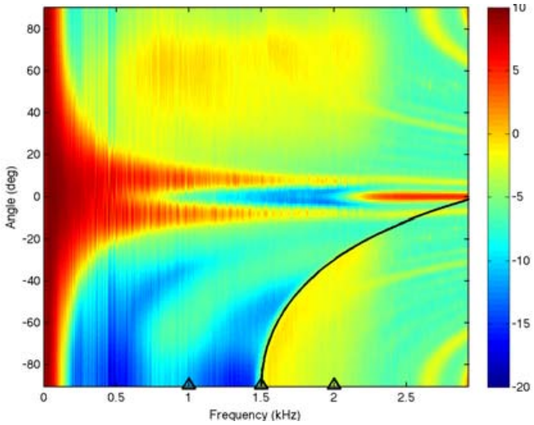

Fig. 2. Beamformer output (dB) for the Mapex2kbis data. The grating lobes curve (solid) is in the lower right corner. This is for a 32-element array with d=0.5 m spacing, corresponding to a 1500-Hz design frequency.

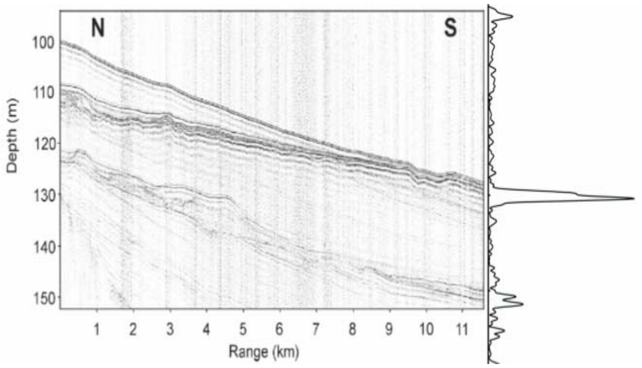

Fig. 4. Seismic section for the Mapex2kbis area [3]. The location of the vertical array is about 1 km further to the south. To the right the extracted reflection sequence, obtained using the WNC-MVDR high-resolution adaptive beamformer on the vertical array data.