Acoustic localization using ice-mounted geophones in the Canadian high Arctic

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INTRODUCTION

The direction to an acoustic source in the open ocean is typically determined by applying beamforming techniques to acoustic pressure fields as measured at an array of hydrophones, or by employing directional hydrophones. In the Arctic, however, deploying hydrophones through the sea ice cover is a laborious task which is difficult to automate or carry out remotely (e.g., from an aircraft). Geophones coupled to the surface of the ice are much more easily deployed and have proven to be sensitive to ocean acoustic fields [1]. However, to date, little work has been reported regarding the capability of ice-mounted geophones to determine source direction (bearing). In theory, a three-component geophone or an array of vertical-component geophones can provide enough information to resolve source direction. In practice, however, the interpretation may be confused by multiple arrivals, by scattering in the rough, inhomogeneous ice layer, and by shear waves in the ice.

EXPERIMENT

To investigate the effectiveness of acoustic localization using ice-mounted geophones, an experiment was carried out on the polar pack ice north of Ellesmere Island, NWT. A linear array of five geophones (three 3-component, two vertical-component), each separated by 20 m, was deployed on the surface of the ice. A simple continuous-wave (CW) source was fashioned by bolting a flexible 6-m metal tube to the exhaust pipe of a diesel generator engine (muffler removed) and lowering the tube into the water through a hole in the ice. A multi-channel digital seismograph was used to record 40-s time series (sampling rate: 500 Hz) when the source was deployed at ranges of 200 m, 500 m and (nominally) 1000 m along lines at 0°, 30°, 60°, and 90° with respect to the array orientation (endfire). The experiment site was characterized by smooth, flat annual ice, approximately 2 m thick; the water depth varied from 18–105 m.

An example of the recorded data is given in Fig. 1 which shows the acoustic power as a function of time and frequency for the source at 855-m range and 90° bearing. Spectral lines are evident at 30 Hz (the cylinder-firing rate of the engine) and 60 Hz, with higher-order harmonics at 30-Hz intervals. The dispersive arrivals at frequencies less than 30 Hz are identified as ambient noise events (plate waves in the ice due to thermal ice cracking or distant pressure-ridge building [2]).

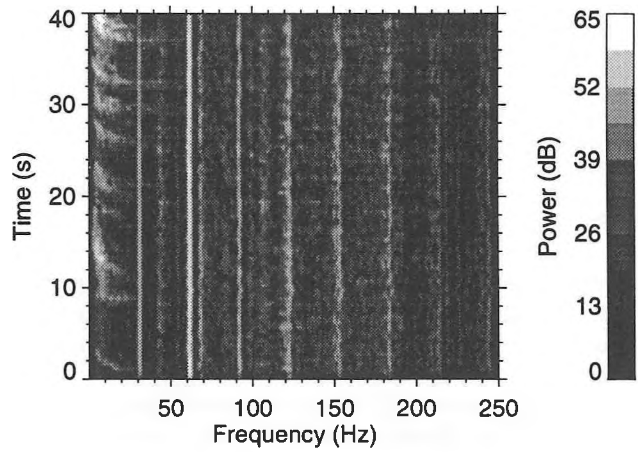

Fig. 1. Time-frequency representation of acoustic power (arbitrary decibels) for the CW source.

ANALYSIS

In this paper, two methods are considered for determining source bearing: principal-component analysis of the horizontal particle motion, and array beamforming of the vertical-component measurements. If the direct (unscattered) compressional wave is the dominate arrival at a 3-component geophone, the particle motion in the horizontal plane should be polarized along a line from source to receiver, providing an indication of the source direction. However, compressional waves that have been scattered at the rough underside of the ice or within the inhomogeneous ice layer and shear waves in the ice produce particle motion that is not polarized in the source direction and degrades the bearing estimate. Principal component analysis [3] provides an optimal method of determining the principal (symmetry) axis of the particle motion. Fig. 2 shows an example of the particle motion in the horizontal plane for a source at 60° and 200 m. The dashed line indicates the principal axis of the particle motion. The principal axis is at an angle of 58° and provides a good estimate of the true source bearing (dotted line). Fig. 3 shows the estimated bearing angles for all source locations. In each case, the recorded 40-s time series were divided into ten 4-s samples which were analysed individually to provide a mean bearing estimate and a standard deviation about the mean. Fig. 3 shows that reasonably good bearing estimates are obtained at a 200-m range;

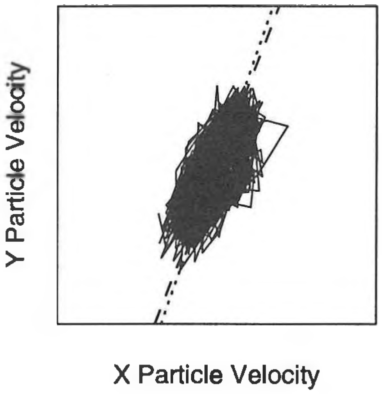

Fig. 2. Horizontal particle motion for a source at 60° and 200 m. Dashed line indicates the principal axis; dotted line is the true bearing.

however, the estimates degrade rapidly with range.

A second approach to determining source direction is to apply plane-wave array beamforming techniques [4] to the vertical-component recordings. The smallest acoustic wavelength that is not spatially aliased in beamforming analysis is given by twice the sensor separation: for the 20-m sensor spacing used here, this corresponds to frequencies <35 Hz. Fig. 4 shows the results of frequency-domain beamforming at 30 Hz for the acoustic source at 500 and 1000 m (the results for the source at 200 m were poor, due to violation of the plane-wave assumption for this short range). Good estimates for source bearing are obtained at 90° and 60° for both ranges, with the main lobe approximately 5 dB above the side lobes (the symmetry about 0° results from using a linear array). At 30° and 0° the beamforming results indicate a source bearing in the interval ±30°, reflecting the decrease in beam resolution with angle and the interpretation of the vertical grazing angle as a horizontal angle near endfire. Considering the small array and short propagation ranges of the experiment, the beamforming results indicate that determining source direction using an ice-mounted geophone array is a promising approach.

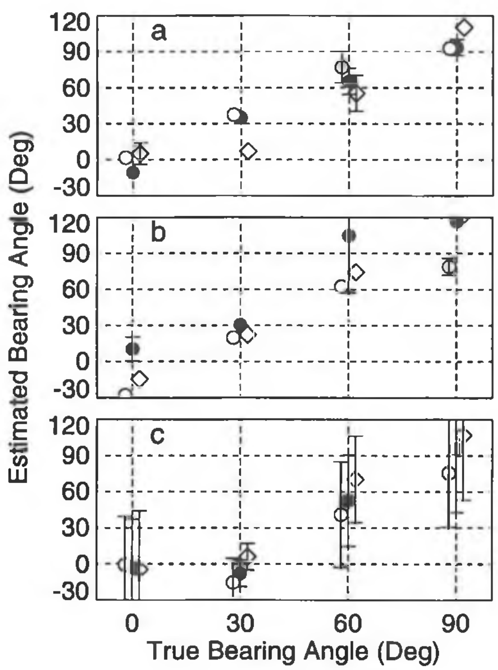

Fig. 3. Bearing angle estimates from principal-component analysis for sources at: (a) 200 m, (b) 500 m and (c) 1000 m. Different symbols indicate estimates for the three 3-component geophones. Error bars (plotted when larger than the symbol) indicate standard deviations.

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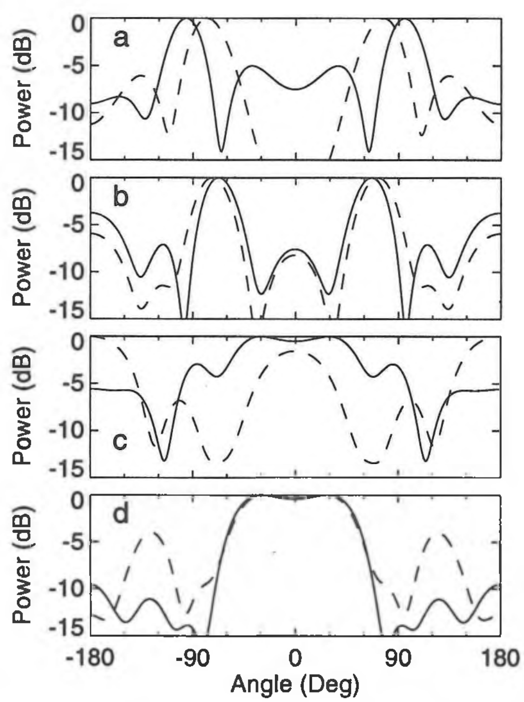

Fig. 4. Beamforming results for source at 500-m range (dashed line) and 1000-m range (solid line) and bearings of: (a) 90°, (b) 60°, (c) 30° and (d) 0°.