FIELD TRIALS OF GEOPHONES AS ARCTIC ACOUSTIC SENSORS

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1. INTRODUCTION

This paper considers two practical issues concerning the use of ice-mounted geophones as Arctic acoustic sensors: the ability to resolve the relative bearing to an acoustic source in the water column, and the ability to determine absolute sensor bearing via short baseline GPS. Two approaches to bearing estimation are compared, including beamforming seismo-acoustic arrivals at an array of geophones and resolving the incident power versus arrival angle at a tri-axial geophone [1, 2]. The latter approach is preferable logistically, as it requires only a single sensor. However, due to the complexities of seismo-acoustic propagation in Arctic pack ice, it is difficult to predict *a priori* the effectiveness of these approaches, and source-bearing estimation must be studied *in situ* via Arctic field trials.

2. FIELD TRIALS

A linear array of five geophones, spaced at 20-m intervals, was deployed by hand on the surface of a 4.5-m thick multi-year ice floe in the Lincoln Sea. The three sensors at the centre of the array were tri-axial geophones; the two outer sensors were vertical-component geophones. The geophone signals were transmitted via over-ice cables to a heated tent and recorded on a 12-channel digital seismograph at a sampling rate of 2000 Hz (results shown here are low-pass filtered 0–200 Hz since the geophone instrument response is unreliable at higher frequencies). Impulsive acoustic sources were deployed at 18-m depth in the water column at ranges of 2, 5, 10, and 25 km and bearings of 0°, 30°, 60°, and 90° (with respect to the geophone array axis) and at 50-km range and 60° and 90° bearing. Source deployments involved drilling through the ice with a power auger, and moving between sites using a helicopter with GPS positioning. The ice cover was continuous in the study area.

3. RESULTS

Figure 1 shows the source-bearing estimates obtained by beamforming the seismograms recorded at the five vertical-component geophones. An analysis of the optimal wave-propagation speed for the beamforming yielded a speed of 1439 m/s, consistent with the average water-column sound speed, indicating that the dominant propagation path consists of water-borne acoustic waves coupling locally into ice seismic waves near each geophone. Symmetry produces an ambiguity in the beamforming results about the array axis, represented in Fig. 1 by two arrows on each panel indicating the ambiguous optimal bearing estimates. Figure 1 shows that the beamforming results are relatively poor for bearings of 0° (endfire to the array), but improve substantially towards 90° bearing (broadside). The bearing estimates and the beamformer angular responses do not appear to degenerate significantly as the source range increases from 2 to 50 km.

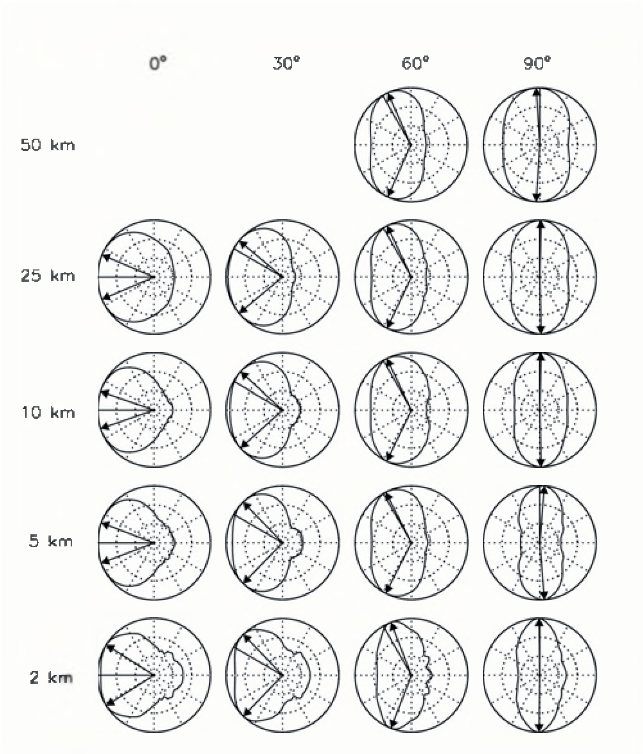

Fig. 1. Beamforming bearing estimates (source bearings and ranges indicated on figure). Solid curves represent beamformer power as a function of look angle from 0–360°; dotted circles indicate 5 dB intervals. True and (ambiguous) estimated source bearings are indicated by solid lines and arrows, respectively.

Figure 2 shows the bearing-estimate results obtained from rotational analysis of particle motion at a single tri-axial geophone (results are shown for the centre geophone, although similar results were obtained for all three tri-axial sensors). The rotational analysis consists of geometrically combining the horizontal seismograms to compute the wave

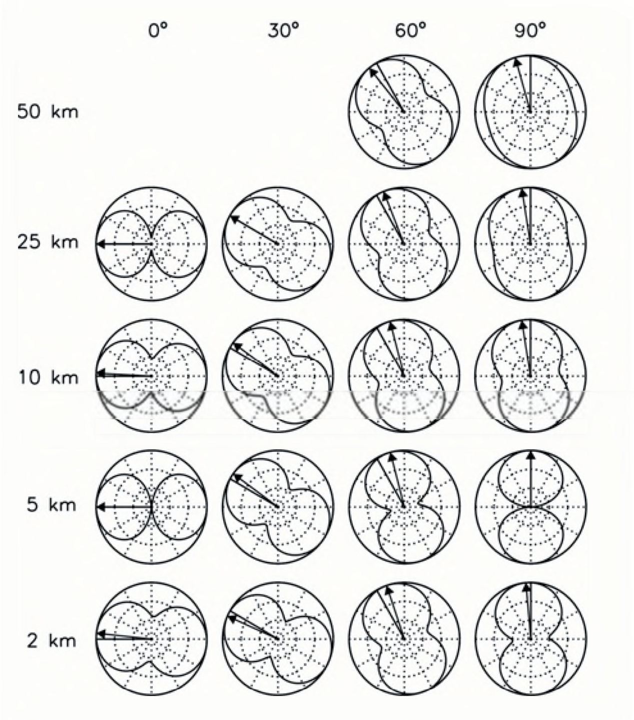

Fig. 2. Bearing estimates from rotational analysis. Solid curves represent signal power as a function of bearing angle; true and estimated bearings given by solid lines and arrows.

power in radial look angles from 0–360° (plotted as solid curves). This analysis is enhanced by applying seismic polarization filters, originally developed for earthquake seismology [3]. These filters make use of theoretical phase relationships between the vertical and horizontal components of the various wave types to selectively suppress waves with transverse particle motion (e.g., shear waves) which degrade the rotational analysis, while passing waves with radial particle motion. In addition, with three-dimensional measurements the 180° ambiguity inherent in the rotational analysis can be resolved by requiring outgoing (prograde) particle motion in the vertical-radial plane, providing a unique bearing estimate (indicated by arrows in Fig. 2). Figure 2 shows that bearing estimates of similar quality are obtained for all source bearings, and that bearing estimates do not degrade significantly with range.

The results for the two approaches to bearing estimation are summarized in Fig. 3, neglecting the ambiguity in the beamforming results. At source bearings of 0° and 30° (at and near endfire), the single-sensor rotational analysis provides substantially better results than array beamforming, with average bearing-estimate errors for rotational and beamforming analyses of 3° and 24° at 0° bearing, respectively. However, beamforming generally produces better bearing estimates for sources at 60° and 90° (broadside), with rotational and beamforming analyses yielding average errors of 8° and 2° at 90°, respectively. Considering all recordings, the rotational and beamforming analyses produced average source-bearing estimation errors of 6.8° and 10.2°, respectively. Given the additional ability to provide a unique bearing estimate and the logistical advantages to using a single sensor, rotational analysis at a tri-axial geophone appears to be the superior approach for source-bearing estimation in the Arctic.

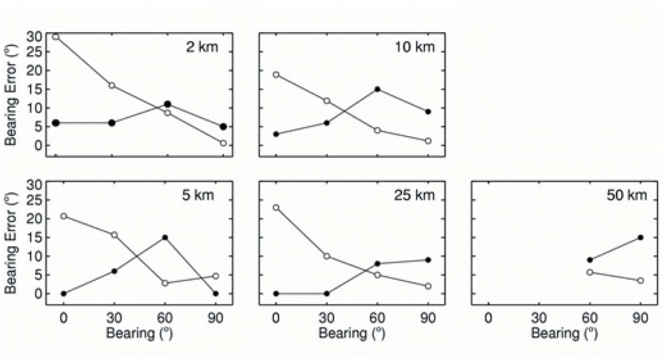

Fig. 3. Bearing estimate errors for rotational analysis (solid circles) and beamforming (open circles).

Given the ability to estimate the bearing to an acoustic source relative to the horizontal components of a tri-axial geophone, the absolute orientation of the sensor is required to obtain the source bearing in geographical coordinates. In the case of the absolute bearing determination for geophone sensors, the practical limitations dictate that the GPS antennas be mounted directly on the top of the sensor, which has a diameter of approximately 10 cm. This limits the bearing accuracy that can be achieved due to carrier phase noise, multi-path, and antenna phase-centre errors. A real-time heading determination algorithm using a double-difference carrier phase approach and integer ambiguity resolution on-the-fly was developed to determine the three-dimensional vector between two GPS antennas [4]. Arctic field trials indicate that this approach can resolve absolute bearing at high latitudes (83° N) to uncertainties of less than 3° employing only low-cost commercial antennas with separations of as little as 4 cm.

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