MARINE MAMMAL SCIENCE, 19(4):708–723 (October 2003)

LOCALIZATION OF NORTH ATLANTIC RIGHT WHALE SOUNDS IN THE BAY OF FUNDY USING A SONOBUOY ARRAY

MARJO H. LAURINOLLI
ALEX E. HAY
Dalhousie University,
Department of Oceanography,
Halifax, Nova Scotia B3H 4J1,
Canada
E-mail: marjo@phys.ocean.dal.ca

FRANCINE DESHARNAIS
Defence Research and Development Canada–Atlantic,
P. O. Box 1012, Dartmouth, Nova Scotia B2Y 3Z7, Canada

CHRISTOPHER T. TAGGART
Dalhousie University,
Department of Oceanography,
Halifax, Nova Scotia B3H 4J1, Canada

ABSTRACT

A free-drifting 14-sonobuoy array was used to localize North Atlantic right whales (*Eubalaena glacialis*) in the Grand Manan Basin area of the Bay of Fundy. This area is a primary summer/autumn right whale habitat and overlaps an international shipping lane. The three-hour deployment on a single day provided two-dimensional localization of 94 right whale sounds based on arrival time differences determined from spectrogram cross-correlation analysis. The sounds were of two distinct types: tonal and gunshot. Maximum detection distances were about 30 km for both types of sound. The mean RMS location error was 1.8 km for tonal-type sounds and 2.5 km for gunshot-type sounds. The average RMS error was 20% of the average distance from the receiving hydrophones, the primary source of error being uncertainty in the sonobuoy positions.

Key words: right whale, *Eubalaena glacialis*, localization, Bay of Fundy, sonobuoys.

The North Atlantic right whale (*Eubalaena glacialis*) population has been protected from whaling since 1935, but still numbers fewer than 350 (Knowlton *et al.* 1992), and the species is considered the most endangered large cetacean in the world (Aguilar 1986, Perry *et al.* 1999). The population was estimated to be declining at 2.4% per year in 1999 (Caswell *et al.* 1999). Since 1970, at least 35%

of documented right whale deaths have been attributed to ship collisions (Laist *et al.* 2001) and another 5% resulted from fishing gear entanglements (Kenney and Kraus 1993). Recovery of the North Atlantic right whale population is thought to depend on the reduction of anthropogenic mortality (Kraus 1990, Caswell *et al.* 1999).

The Bay of Fundy is a primary summer and autumn feeding and nursery habitat for North Atlantic right whales, and one half to two-thirds of the population can be observed annually in the Bay.[1] At least 14 of the 27 surviving calves born in 2001 arrived with their mothers in the Bay for summer and autumn feeding in the same year.[2] The Canadian Right Whale Conservation Area in the Bay overlaps an internationally designated shipping lane used by numerous large carriers (including fuel tankers and container ships). Of the 16 documented deaths due to collision with ships prior to 2000, three likely occurred in the Bay of Fundy; one in each of 1992, 1995, and 1997.[1] Existing measures for reducing ship-strike risk are based on aerial and vessel surveys to determine whale locations, but logistics, visibility, weather conditions, and cost limit their utility (Matthews *et al.* 2001).

An alternative and potentially more effective method for locating whales could involve passive acoustic monitoring. Watkins and Schevill (1972), Clark (1980), Cummings and Holliday (1985), and McDonald *et al.* (1995) among others, have used hydrophone arrays to locate whales. Watkins and Schevill (1972) reported 20 right whale locations using a non-rigid floating four-hydrophone three-dimensional array attached to a drifting vessel. There has not been a study published on North Atlantic right whale localization since.

The annual recurrence of high numbers of right whales for extended periods in the conservation area in the Bay of Fundy provided an opportunity for testing the feasibility of passive acoustic localization techniques for right whales in this critical habitat area. The purpose of this paper is to present results from a pilot localization experiment using a freely drifting eight-element sonobuoy array in the Bay.

Methods

Sonobuoy Array

On 29 July 1999, 17 sonobuoys were air-deployed in Grand Manan Basin, Bay of Fundy (Fig. 1). The area from 66.3°W to 66.58°W and 44.5°N to 44.75°N has been designated as the Canadian Right Whale Conservation Area (620 km^2). Approximately one-half of the area overlaps the present location of the shipping lane to Saint John, NB. On the day of the deployment, the Bay was blanketed with fog (visibility varied from 20 m to 500 m), the sea was calm, and there was little wind (0–1 Beaufort). Right whales were known to be in the lower Bay from sightings made from the R/V *Nereid* which surveyed the area between 66.45°W and 66.52°W and 44.62°N and 44.65°N during the deployment period. Other species of whales were not sighted although minke (*Balaenoptera acutorostrata*), humpback (*Megaptera novaeangliae*), fin (*Balaenoptera physalus*), and sei (*Balaenoptera borealis*) whales are known to frequent the Bay of Fundy.

[1] Technical report by A. Knowlton, P. Hamilton, S. Kraus and M. Brown. (2000). Right whale research and conservation efforts in the lower Bay of Fundy: 1999. Available from New England Aquarium, Central Wharf, Boston, MA 02110.

[2] Personal communication from Moira Brown, Center for Coastal Studies, P. O. Box 1036, Provincetown, MA 02657, August 2001.

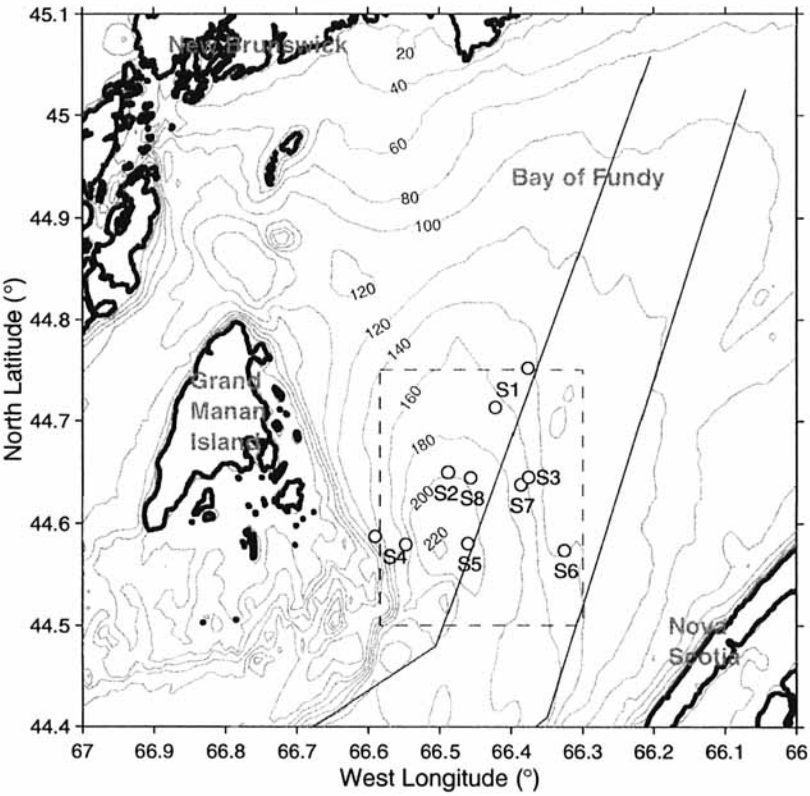

Figure 1. Bathymetric (20-m isobaths) chart of the Bay of Fundy showing the Canadian Right Whale Conservation Area (dashed rectangle) in the Grand Manan Basin region (140 m depth), the shipping lane (solid lines), and the deployment stations for the tracked sonobuoys where each station, labelled S1–S8, consisted of between one and three sonobuoys.

Four sonobuoy types were used: six AN/SSQ-57Bs, five AN/SSQ-53D DIFARs, three AN/SSQ-53E DIFARs, and three modified AN/SSQ-525A VLAs. Most of the sonobuoys had a receiver bandwidth from 10 Hz to 2.4 kHz, while the AN/SSQ-57B sonobuoy bandwidth extended up to 40 kHz. The sonobuoys were dropped in a 160-km^2 triangular pattern of six stations, designated as S1–S6 (Fig. 1), with groups of three sonobuoys at each apex and two sonobuoys at the midpoints of the sides of the triangle. Single sonobuoys were deployed at S7 and S8 approximately 1.5 h after the others, closer to the right whales sighted from the R/V *Nereid.* The sonobuoy hydrophone depths were set to 30 m below the surface. A total of 39 h of sonobuoy data summed over all 17 sonobuoys were recorded, of which 13.6 h were not useable either because the signals were corrupted by land-based radio signal interference, or because of sonobuoy failure. Thus, 25.4 h of useable data were recorded on 14 functioning sonobuoys.

A radio frequency (RF) signal tracker on the aircraft was used to locate the sonobuoys to about 100-m accuracy. Position updates were available for only 10 sonobuoys and the S5 location had no tracking available for the latter half of the deployment. Positions for this station were therefore extrapolated using S7, its nearest neighbor. Each of the other seven stations had at least one sonobuoy that was tracked from deployment to the end of the recording period. At each station with more than one sonobuoy, the sonobuoys without position updates were assumed to be located at the same positions as the tracked sonobuoys at the same drop stations.

Data Collection and Processing

The sonobuoy radio-telemetry signals were received by aircraft and recorded on 28-track magnetic tape. The recording period was approximately three hours, between 1300 and 1600 UTC (Coordinated Universal Time; 1000–1300 ADT). The recorded signals were passed through antialiasing filters with a cut-off frequency of 3,277 Hz, digitized at a sampling frequency of 6,554 Hz, and stored on digital linear tapes (DLT). Five-minute SUN audio files were created using IDL5.3 (Interactive Data Language, Research Systems Inc.).

The audio files from all 17 sonobuoys were aurally analyzed for the presence of whale sounds. The spectrograms of these detected sounds were compared to southern right whale sounds described by Payne and Payne (1971) and Clark (1982, 1983). The comparisons were favorable in terms of both frequency signatures and durations and, thus, the detected sounds were presumed to be those of right whales. The time of each whale sound was tabulated, and each sound was classified as "loud" or "weak." The audio files were imported into Matlab (The MathWorks, Inc.) for processing on a Sun Ultra workstation. Twelve-second spectrograms of 5 Hz and 6 msec resolution (1,311-point FFT, Hanning window, 98% overlap) were created starting approximately 2 sec before each sound.

Historical records of July–August hydrographic data from the Grand Manan Basin area (43.3°–45.5°N and 65.6°–67.5°W) spanning the last 90 yr (compiled and revised at the Bedford Institute of Oceanography and obtained from the Marine Environmental Data Service) were used to estimate sound speed following Mackenzie (1981). Air-deployed expendable bathythermographs (AXBT) dropped during the experiment provided low resolution data and thus were not used. Salinities in the area ranged from 30‰–35‰.

Localization

Estimated monthly averaged sound speed varied by less than 10 m/sec over the 200-m water depth. Sounds detected were therefore assumed to have traveled by direct path at isovelocity, as in previous whale localization studies (*e.g.*, Cummings and Holliday 1985). A sound speed of 1,490 m/sec was used.

Sounds were localized using a spectrogram cross-correlation technique (*e.g.*, Clark *et al.* 1987, Clark and Ellison 2000). The tabulated arrival times of sounds determined aurally were compared to identify sounds detected on different sonobuoys within a few seconds of each other and were designated as potential sound arrivals from the same sound source. Subsequently, one of the stronger sounds within a group of sounds with similar arrival times was selected as the primary sound and was used as the one against which the others would be cross-correlated. A time-frequency window was selected from the primary sound spectrogram and a time-lagged, cross-correlation function was computed, using this primary spectrogram window and corresponding windows in the spectrograms from the other sonobuoys. The time-width of the primary windows varied from 0.5 to 3.5 sec for tonal sounds and was about 0.5 sec for gunshots. The frequency height of the windows was 100–200 Hz for tonals and 400–3,000 Hz for gunshots. If the spectrograms were visibly dissimilar, or if there was not a pronounced maximum in the lagged cross-correlation function, the sounds were considered to have come from different sources. Otherwise, the time-lag at maximum cross-correlation provided the estimate of arrival-time difference for the sound.

Hyperbolae of equal time difference were calculated relative to the corresponding sonobuoy-pair positions (Watkins and Schevill 1972, Cummings and Holliday 1987, Spiesberger and Fristrup 1990). For N sonobuoys detecting a given sound, there are $N!/[2!(N-2)!]$ different sonobuoy pairs, and one time difference hyperbola for each pair. Thus, a sound detected on three sonobuoys yields three hyperbolae. Only two of the three time differences are linearly independent, however, and all three hyperbolae intersect at a single point. For sounds detected on three or more hydrophones, $N!/[3!(N-3)!]$, such points of intersection (corresponding to the number of independent combinations of three hydrophones) can be obtained. For example, four hydrophones result in six hyperbolae, and yield four points of intersection, from which a location error estimate can be made. Thus, the average of the intersection points for sounds detected on four or more sonobuoys was taken as the location of the sound source. The error in this location was estimated from the standard deviation of the hyperbolae intersections in the zonal (ε_x) and meridional (ε_y) directions, giving the root-mean-square (RMS) error $\varepsilon = (\varepsilon_x^2 + \varepsilon_y^2)^{1/2}$.

Results

Sonobuoy Drift

The average separation distance between tracked sonobuoys within the array was 12 km at both the beginning of the deployment and two hours later. The sonobuoys drifted approximately 7 km north and 5 km east of their starting positions over the three-hour period, consistent with the flood tide, giving an average drift speed of 2–3 m/sec. The time series of sonobuoy longitude and latitude coordinates were highly coherent, indicating that extrapolation from tracked sonobuoys to obtain positions of untracked sonobuoys should be reasonable for those dropped close together (*i.e.*, at the same station).

Right Whale Sounds

A total of 1,683 right whale sounds were aurally detected in 25.4 h of uncorrupted sonobuoy records summed across 14 functioning sonobuoys. As described below, the whale sounds were classified into five categories, similar to those obtained by Clark (1982) for southern right whales. Four categories were of the general "tonal" type ($n = 255$); the fifth was the broadband or "gunshot"-type sound ($n = 1,428$). Similar broadband sounds detected in the presence of bowhead whales (*Balaena mysticetus*) have been referred to as "gunshot"-type sounds by Würsig and Clark (1993).

The tonal sounds comprised either constant low-frequency ($n = 129$), mid-frequency modulated ($n = 58$), low-frequency upsweep ($n = 38$), or mid-frequency unmodulated ($n = 12$) fundamentals, where the term "low" refers to the 100–200-

Hz band and "mid" to the 200–800-Hz band. These bands were chosen since most of the sounds seemed to be centered near 120 Hz or 500 Hz with few in between, and because noise dominated below 100 Hz. Some tonal sounds were faint and not categorized ($n = 18$). Some sounds designated as tonal were broader band "raspy" sounds and could be considered pulsive or atonal but were designated as tonal here. Clark (1982) designated tonal sounds having small frequency change as "constant calls" and those consisting of low frequency upsweeps as "contact calls." Many tonal sounds included several harmonic frequencies. Most of the tonal sounds had durations of 0.5–1.5 sec. The constant low-frequency sounds were generally of longer duration (up to 2 sec).

The gunshot-type sounds are broadband, short-duration (0.2 sec) transients, and are similar to various slapping sounds described by Clark (1983), and to the gunshot-type sounds described for bowhead whales by Würsig and Clark (1993). Some of the broadband sounds we recorded are suspected to be of "vocal" origin with an unknown production mechanism.[3]

Of the total of 255 tonal sounds in the sonobuoy recordings, 217 were "loud" and easily recognized in the spectrogram. The signal-to-noise ratios of the received spectral density levels for the tonal sounds identified in this way were all greater than 5 dB. Of the 1,428 gunshots, 747 were clearly visible in the spectrogram. Considering only those sounds that were visually identifiable in this way, the average frequency of occurrence of tonal sounds was 0.1 min^{-1} and that of gunshots was 0.5 min^{-1} across all sonobuoys summed together. Including all aurally detected sounds, both loud and weak, the frequencies of occurrence were 0.2 min^{-1} and 0.9 min^{-1} for tonal- and gunshot-type sounds, respectively.

Locations and Location Accuracy

Two examples of auto and cross-correlation functions for tonal sounds are shown in Fig. 2. For the tonal sounds, the correlation functions were computed from the signal-to-noise (SNR) spectrograms using linear spectral densities (*i.e.*, not in logarithmic (dB) spectral densities as shown in Fig. 2a, d). The first sound shown, a low-frequency upsweep, has a sharp autocorrelation peak (see Fig. 2b). The second sound sample is a nearly constant-frequency sound of longer duration and therefore has a broader autocorrelation peak (see Fig. 2e). This indicates that localization accuracy will be lower for constant-frequency tonal sounds than for frequency-modulated tonal sounds. Each sound was cross-correlated against the same sound on two other sonobuoys. The lagged cross-correlation function peaks are somewhat broader and lower in magnitude than the autocorrelations, as expected. The double-peak at about 3-sec lag in Fig. 2c may be due to the presence of two acoustic modes.

For the gunshot sounds (Fig. 3) it was found that better results (sharper correlation peaks) were obtained when the correlation functions were computed using spectral densities on a logarithmic (dB) scale. Taking the logarithm of the spectral densities effectively resulted in a smoother spectrum by reducing the amplitude of the variability in these broadband spectra. Overall, the peaks in the lagged correlation functions for gunshots in Figure 3b, c are sharp and quite distinct.

Of the 217 "loud" tonal sounds distributed across the 14 sonobuoys that

[3] Personal communication from Susan Parks, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, August 2000.

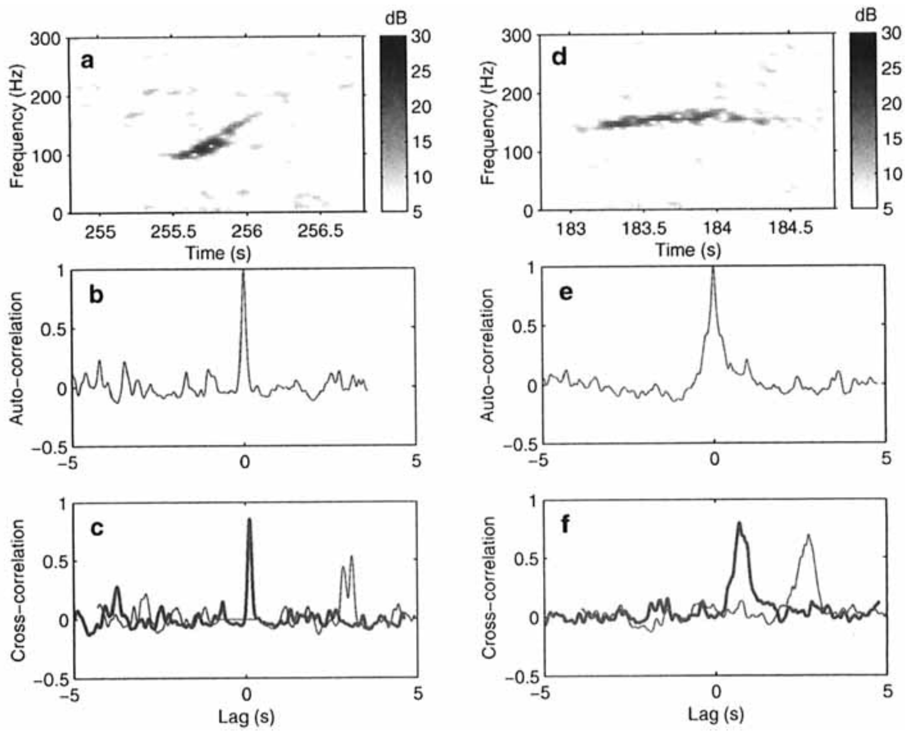

Figure 2. Top panels show two example tonal spectrograms (gray scale indicates signal-to-noise in dB): (a) low-frequency upsweep and (d) constant low-frequency sounds. Panels below are the corresponding auto-correlations (b, e) and cross-correlations (c, f) with the same sound on other sonobuoys. The locations of the peaks in (c) and (f) represent the lag in sound arrival time on the other two sonobuoys. Correlations were calculated in linear spectral density space (antilog of dB).

successfully recorded underwater sound, 76 were used to obtain 22 source locations (mean = 3.5 sonobuoys per location estimate). These sources consisted of eight constant low-frequency sounds, six mid-frequency modulated sounds, six low-frequency upsweep sounds, and two mid-frequency, non-modulated sounds. Of the 747 gunshots detected, 306 were used to produce 72 source locations. Thus, on average, the located sounds (gunshot and tonal types combined) were detected on four sonobuoys (382/94). Approximately 40% (382/964) of all "loud" sounds detected (tonals and gunshots combined) were localized. The maximum detection distances for tonal and gunshot sounds were 28.6 km (mean = 10.3 ± 5.5 km) and 33.0 km (mean = 10.1 ± 5.2 km), respectively.

The majority of the sound source locations were northeast of the area surveyed by the R/V *Nereid* during the deployment period and thus northeast of the nine visual right whale sightings (Fig. 4). Approximately 70% (77% of tonals and 68% of gunshots) of the 94 located sounds were in the shipping lane during this short time period on a single day. Most of the whales were in 120–180 m deep water. Half of the localizations (91% of tonals) were obtained during the final hour of recording when the sonobuoys were in the northern half of the conservation area. Thus, the

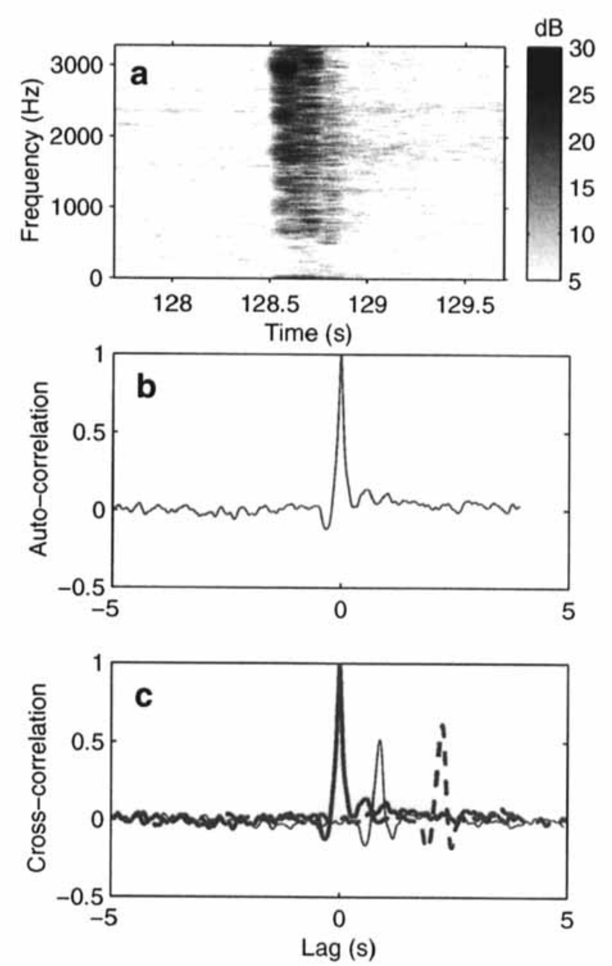

Figure 3. Top panel is an example gunshot spectrogram (gray scale indicates signal-to-noise in dB). Panels below are the corresponding auto-correlation (b) and cross-correlation (c) with the same sound on other sonobuoys. The locations of the peaks in (c) represent the lag in sound arrival time on the other three sonobuoys. Correlations were calculated with spectral densities on a logarithmic scale (dB).

pattern of whale locations was partly related to the array configuration, sonobuoy drift and sonobuoy recording quality.

Relatively large differences sometimes occurred among the intersections for the different sets of three hyperbolae for a given sound (Fig. 5). The differences in this example are primarily related to uncertainty in locations of sonobuoy #5 (at S2) and #14 (at S6) for which tracking had to be extrapolated from other sonobuoys. The source position is estimated to be the average of the four intersections marked with square symbols (Fig. 5), and the error is estimated as described previously.

The mean RMS error (Fig. 6) for all localizations obtained using four or more sonobuoys was 1.8 km for tonals ($n = 8$) and 2.5 km for gunshots ($n = 49$). The

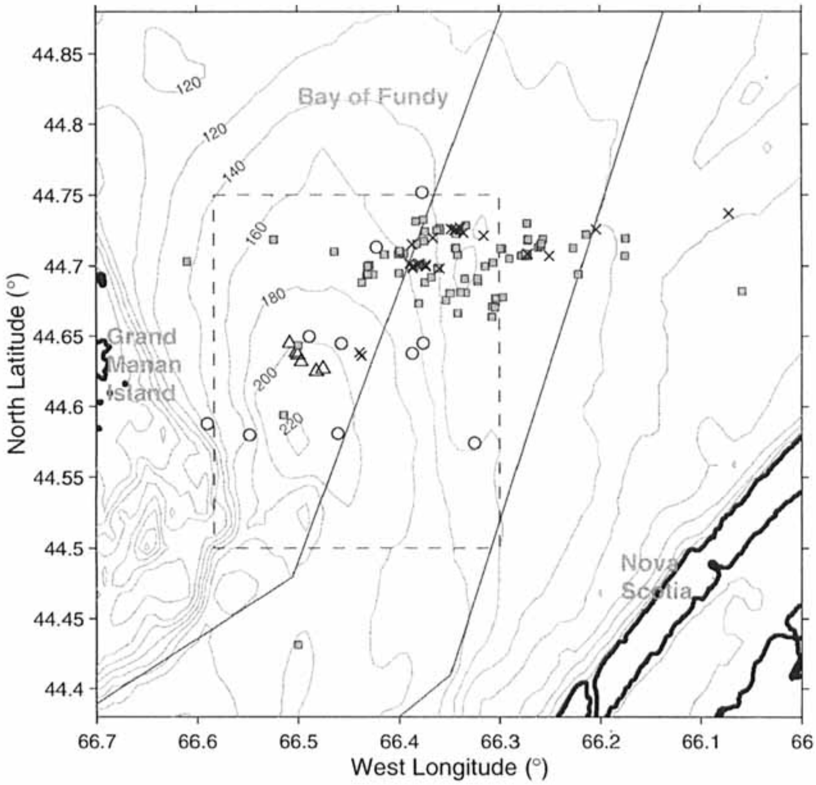

Figure 4. Bathymetric (20-m isobaths) chart of the Grand Manan Basin region in the Bay of Fundy showing right whale sound locations determined by passive acoustic localization (squares: "gunshot" sounds, $n = 72$; crosses: "tonal" sounds, $n = 22$), and visual sighting (triangles) of right whales from R/V *Nereid* on 29 July 1999. The initial positions of the sonobuoys are shown as circles.

RMS error tended to increase with mean distance from the receivers when all 57 locations were considered. The average RMS error was 20% of the average distance from the receiving hydrophones. Location errors increase rapidly outside an array as the target-to-receiver distance becomes much greater than the spacing between receivers (Watkins and Schevill 1972, Wahlberg 1999). The maximum RMS error for gunshots was 8.6 km at a range of 33.0 km and 3.3 km at a range of 10.3 km for tonals. An increase in RMS error with range is not evident in the tonal sound locations alone as the eight locations with error estimates were at a similar range. The lack of error estimates at average ranges below 5 km is due to the use of "average range" and the array geometry. The average sonobuoy separation was about 12 km. If a whale were in the center of a triangular sonobuoy array, 12 km on a side with a sonobuoy at each apex and at the midpoint of each side, the shortest average distance possible to the sonobuoys would be 5.2 km, which is consistent with the minimum range of 5.3 km in Figure 6.

The standard deviations in longitude and latitude in intersections are shown in Figure 7. Points without error bars were determined using only three sonobuoys

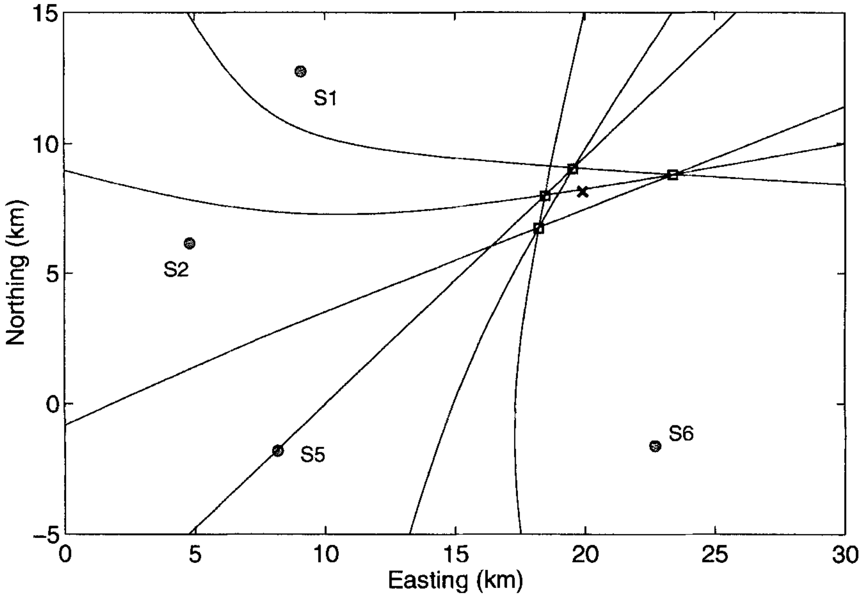

Figure 5. Example of a right whale sound localization showing relatively large error based on intersections of equal time difference hyperbolae (calculated relative to sonobuoy-pair positions; S1, S2, S5, and S6). The sound location (X) is the average of the four intersections (squares).

(one intersection). The mean standard deviation errors in the zonal (ε_x) and meridional (ε_y) directions were 2.0 km and 1.2 km, respectively, for gunshots. For tonals, $\varepsilon_x = 1.6$ km and $\varepsilon_y = 0.8$ km. Targets located farthest to the east may be in error by several kilometres due to the inaccurate sonobuoy positions and because the intersecting hyperbolae become almost parallel at large distances from the sonobuoys. Whereas the bearings are likely accurate, the same cannot be said for the ranges.

Discussion

Here we compare the present localization results to results obtained in other studies for right whales and other large whales. Other studies have not localized on the gunshot-type sounds, so this discussion is confined primarily to tonal-type sounds.

The bowhead whale (*Balaena mysticetus*) is closely related to the right whale. Cummings and Holliday (1987) studied bowhead whales off Alaska with a nearly linear, 2.46 km long, three-element sonobuoy array fixed to the landfast ice edge. They recorded 7,502 whale sounds and were able to locate 202, of which 80 were considered to be of "high confidence." This represents a localization success rate of 8% (202/(7,502/3)) for all locations, or 3% for highly confident locations, compared to our 35% success rate for all, or 41% for "loud" tonal-type sounds. Cummings and Holliday (1987) recorded 30 times more sounds than the present study, but only nine times the number of localizations. Although the

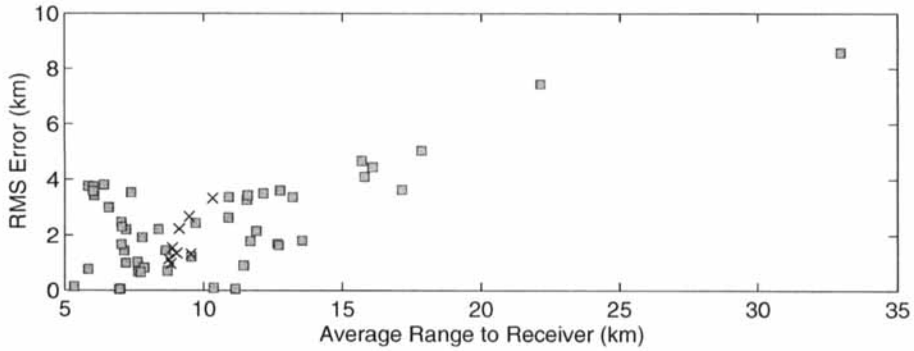

Figure 6. Root-mean-square (RMS, km) error in hyperbolae intersections as a function of average range (km) to the four or more sonobuoys used to estimate the locations of right whale sounds (squares: "gunshot" sounds, $n = 49$; crosses: "tonal" sounds, $n = 8$).

two-dimensional array geometry and larger number of array elements used in the present study might be partly responsible for our higher localization success rate, Cummings and Holliday (1987) suggested that their inability to localize more sounds was likely due to ambient noise, not array size or multipath sound travel, and in the their shallow (19 m) water depth, low-frequency moans were noise-limited beyond 2.5 km and songs beyond 10.7 km.

Cummings and Holliday (1987) recorded their 7,502 bowhead sounds over a 158.2-h period. Presuming that this value includes all three hydrophones, they obtained 0.3 sounds min^{-1} per hydrophone. In our study, with 25.4 h of clean data on 14 sonobuoys, we have an average recording period of 1.8 h. Thus, the 255 tonal sounds detected correspond to a frequency of occurrence of 0.17 min^{-1} per hydrophone for all tonal sounds (0.14 min^{-1} per hydrophone for the "loud" tonal sounds). Thus, the rates obtained here for non-migrating right whales are similar to the reception rates obtained by Cummings and Holliday for migrating bowheads.

Other studies of North Atlantic right whale sounds in areas where the whales are concentrated have reported sound reception rates of $<$1–12 min^{-1} in 65.6 h of recordings (Matthews *et al.* 2001) and 0.3–0.7 min^{-1} in 2 h (Vanderlaan *et al.* 2003). Payne and Payne (1971) reported 0.03 min^{-1} in 9 h of daytime recordings near a small concentration of southern right whales and 1 min^{-1} in 3 h of nighttime recordings off Peninsula Valdez, Argentina. Thus, our sound reception rate is comparable to other reported values for right whales.

Watkins and Schevill (1972) achieved good localizations to a range of ten times their non-rigid array dimension of 30 m and highly confident localizations to a range of three to four times the array dimension. The localizations reported here are at ranges up to two to three times the mean sonobuoy separation.

The average RMS range error estimated here (approximately 1 km, or maximum RMS error of 23% of the maximum range) is comparable to other studies. Cummings and Holliday (1987) reported an average predicted maximum range error of 26.5%, based on a maximum sound arrival time difference error of 10 msec and a maximum array aperture ambiguity at 30° from the baseline. Watkins and Schevill (1972) reported an error of only 1 m within their 30-m array but an error of 25% at a distance of 80 m and 50% at 300 m, the maximum range of their localizations.

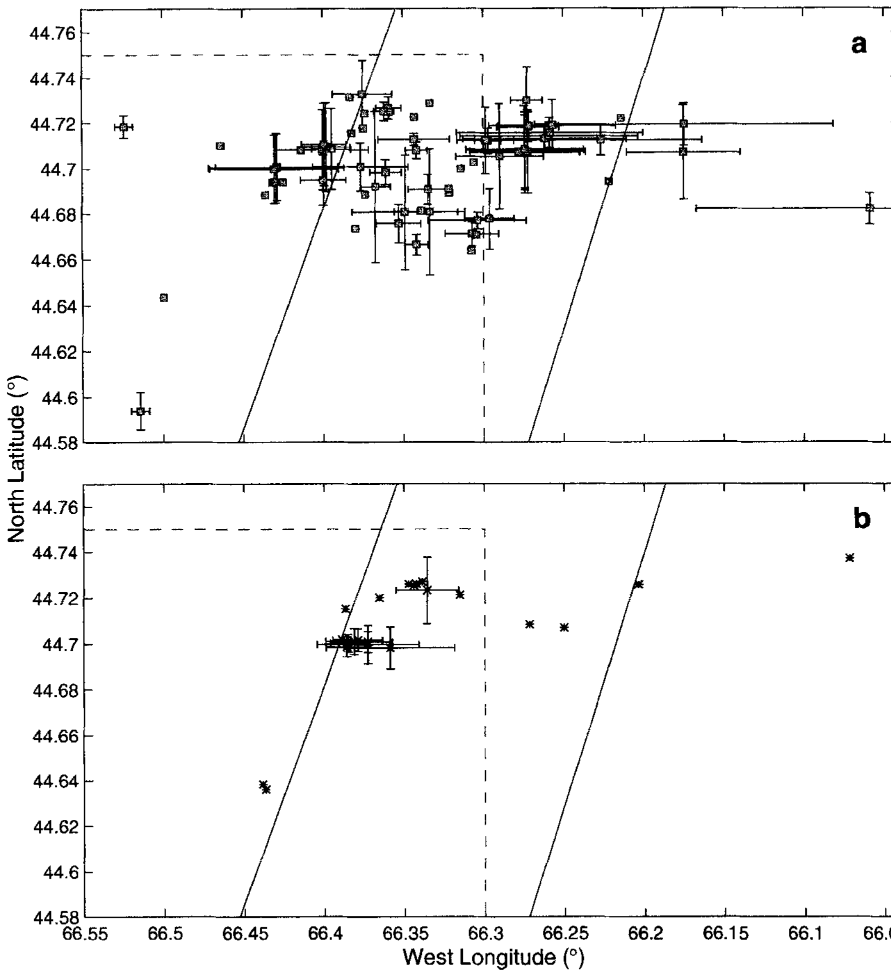

Figure 7. Estimated right whale sound locations with one standard deviation (SD) error bars of the hyperbolae intersections in both the zonal and meridional directions: (a) "gunshot" sounds (n = 49) and (b) "tonal" sounds (n = 8). Points without bars resulted from localization with only three sonobuoys (dashed box: conservation area; solid lines: shipping lane).

In the present study errors in the time differences obtained from the spectrogram correlation method, or due to the assumptions of uniform sound speed and two-dimensional sound propagation, are considered to be insignificant relative to the errors in hydrophone position. Although waveform correlation (Clark and Ellison 2000) could in principle produce more accurate results, especially for constant-frequency tonal sounds, it is unlikely, given our sonobuoy position uncertainty, that the improvement over the spectrogram correlation method would be significant. As evidence to support this view, preliminary results from our use of a bottom-mounted hydrophone system indicate that right whale sounds can be located with less than a few hundred meters probable error if hydrophone locations are known to a greater degree of accuracy than in this sonobuoy study (Fig. 8).

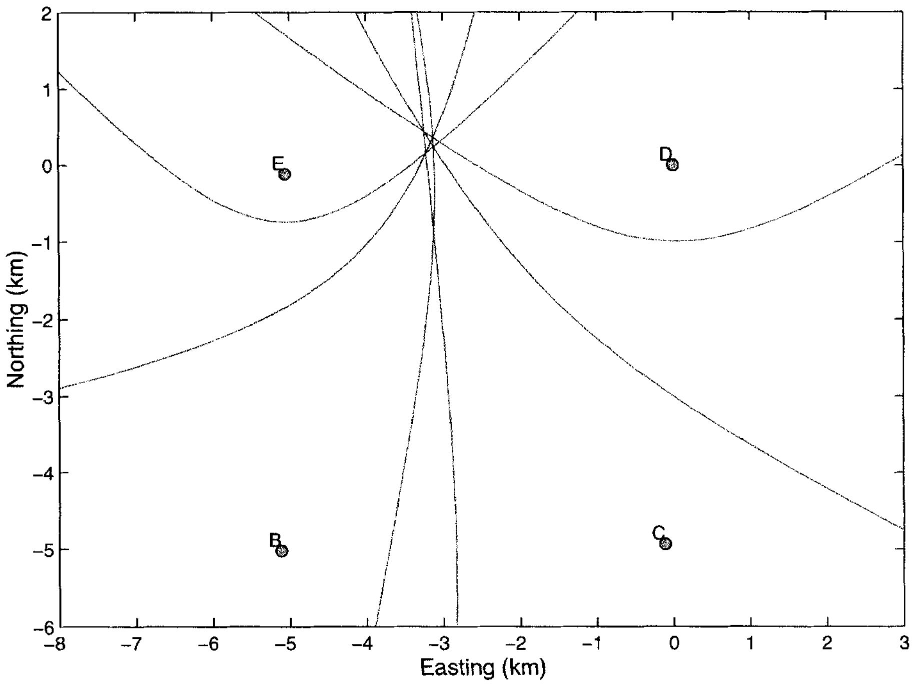

Figure 8. Example of a right whale sound localization showing relatively small error based on intersections of equal time difference hyperbolae using the more accurate position information provided by four bottom-mounted hydrophones B, C, D, and E deployed in the Grand Manan Basin region.

The data obtained in this study have potential for a variety of other analyses. In particular, the received sound levels and source-receiver distances obtained here can be combined with transmission loss models to obtain estimates of right whale sound source levels (Hay *et al.* 2002). The DIFAR sonobuoys deployed in this study could also be used to obtain bearings to the source, potentially reducing the location error. Three-dimensional localization was not attempted due to the inaccuracy in the sonobuoy locations. This problem could be addressed with the use of inversion techniques such as those employed by Dosso and Collison (2002).

Conclusions

The majority of right whale sound locations obtained in this study were distributed along a roughly east-west axis extending from the northeast corner of the Right Whale Conservation Area into the shipping lane (Fig. 4). Many of these locations are farther east than expected based on the decadal average of visual sightings.[4] Murison and Gaskin (1989) also reported visual sighting data for right

[4] Briefing note, draft three by M. Brown, R. Kenney, C. Taggart, A. Vanderlaan, J. Owen, J. Ring, A. Knowlton, and S. Kraus (2001). Measures to reduce interactions between the endangered North Atlantic right whale and large vessels in the waters of Atlantic Canada. Prepared for the Canadian Marine Advisory Council, Standing Committee on Navigation and Operations, Ottawa, ON on 7–8 November 2001.

whales in the Bay of Fundy that are more consistent with the western portion of our distribution. Most of the sounds located within the shipping lane were detected within the last hour of the deployment, by which time the sonobuoy array had drifted with the tide to the northeast corner of the conservation area. Thus, a partial explanation for the eastward extent of the sound locations may be related to the sonobuoy drift, and to possible errors in the sound locations arising from sonobuoy position uncertainty. However, it should be noted that Murison and Gaskin surveyed only a 20 × 25-km grid thought to be the "normal summer-fall range" of right whales in the Bay of Fundy and thus did not look for right whales east of 66.3°W. Furthermore, Mate *et al.* (1997) have reported satellite-tracked right whales travelling within and across the shipping lanes and reported a "large number in the shipping channel." Thus, an equally plausible explanation for the difference between the location distribution in Figure 4 and the long-term mean distribution of visual sightings in this area is that the whales are to be found at times within and even east of the shipping lane. Such incursions, which are likely related at least in part to the tide given the strong (>1 m/sec) tidal currents, have clear implications for ship-strike mitigation in this area.

Few of the whale sound locations from the 1999 experiment were in the vicinity of the visual whale sightings made from the R/V *Nereid.* While the vessel did not survey the northeast corner of the Conservation Area, the ability of the personnel on the vessel to make visual sightings was limited by fog. Only nine visual sightings were obtained from the vessel. None were sighted from the aircraft. These numbers, when compared to the 94 locations from the sonobuoy array, serve to underscore the potential value of acoustic monitoring of right whale location distributions in the lower Bay of Fundy, even during daylight hours.

The location errors obtained in this pilot study are primarily due to the limitations of the technologies employed, rather than to any intrinsic limitation of the technique. Thus, the errors in receiver locations can be virtually eliminated either by using fixed bottom-mounted hydrophones or, in the case of a free-drifting array, by using GPS-tracked drifters.

In conclusion, the results from this 3-h pilot experiment indicate that passive acoustic location of right whales in the lower Bay of Fundy is both feasible and informative. Future studies using longer deployment times are clearly warranted. Such studies would serve in particular to clarify the frequency and numbers of right whale incursions into the shipping lane both during the day, and at night.

ACKNOWLEDGMENTS

We thank the 415 Maritime Patrol "Swordfish" Squadron, CFB Greenwood, NS, for air deployment and monitoring of sonobuoys. We appreciate the whale sighting information provided by the crew of the New England Aquarium R/V *Nereid*, the 1999 hydrographic data provided by the Northeast Fisheries Science Center, Woods Hole Laboratory, and the Marine Environmental Data Service historical hydrographic data provided by J. Sheng at Dalhousie University. This research was supported in part by Defence Research & Development Canada–Atlantic, the Environment Canada–World Wildlife Fund Canada Endangered Species Recovery Fund, the Department of Fisheries and Oceans Canada, and the Natural Sciences and Engineering Research Council of Canada. We also thank A. Vanderlaan for useful discussions as well as T. Mudge and D. Schillinger for data processing assistance. We are grateful for the constructive comments by three anonymous reviewers.

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Received: 12 August 2002
Accepted: 21 March 2003