LOCALISATION OF RIGHT WHALE SOUNDS IN THE WORKSHOP BAY OF FUNDY DATASET BY SPECTROGRAM CROSS-CORRELATION AND HYPERBOLIC FIXING

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ABSTRACT

In September 2002, five ocean-bottom hydrophones recorded acoustic data in the Bay of Fundy at 1200 Hz sampling frequency for 165.6 h. Arrival time differences for 15 right whale sounds (5 gunshots, 10 tonals) were determined by spectrogram cross-correlation of logarithmic (i.e. dB re 1 $\mu Pa^2/Hz$) spectral densities. The sound source locations were estimated from the intersections of the linearly independent equal time difference hyperbolae for different hydrophone pairs. The root-mean-square (RMS) localisation error was examined using three sound speeds. The lowest average RMS error of 0.85 km was obtained for 1485 m/s, roughly 7 m/s less than the measured average sound speed. The non-gunshot sounds had greater localisation error than the gunshot sounds by 0.4 km. The mean and maximum ranges from the centre hydrophone in the array were 10 km and 33 km respectively.

RÉSUMÉ

En septembre 2002, cinq hydrophones ancrés au fond marin dans la Baie de Fundy ont enregistré des données acoustiques échantillonnées à 1200 Hz pour une durée de 165.6 h. Des différences de temps d'arrivée pour 15 sons de baleines franches (5 « coups de feu », 10 tonals) ont été déterminés par corrélation croisée de spectrogrammes de densité spectrale logarithmique (i.e. dB re 1 $\mu Pa^2/Hz$). La localisation des sources sonores a été estimée à partir des intersections d'hyperboles linéairement indépendantes de différences temporelles égales pour différentes paires d'hydrophones. La moyenne quadratique (RMS) de l'erreur de localisation a été examinée en utilisant trois vitesses de son. L'erreur RMS moyenne la plus basse (0.85 km) a été obtenue avec 1485 m/s, soit 7 m/s de moins que la mesure moyenne de la vitesse du son. Les vocalisations avaient une plus grande erreur de localisation que les sons « coup de feu», soit 0.4 km de plus. Les distances moyennes et maximales à partir de l'hydrophone central du réseau étaient de 10 et 30 km respectivement.

1. INTRODUCTION

The North Atlantic right whale population is in serious jeopardy from mortalities related to anthropogenic activities (*e.g.* Caswell *et al.* 1999, Perry et al. 1999, Knowlton *et al.* 1992, Kraus 1990). Passive acoustics has been previously suggested for monitoring cetacean location and presence, both by the current authors and others (Laurinolli *et al.* 2003, Mellinger *et al.* 2000, Folkow and Blix 1991, Clark and Fristrup 1997). This method allows for non-obtrusive, round-the-clock observation of whale locations and behaviour, and thus provides a potential means for reduction of ship-strikes and fishing gear entanglements.

A small data set of right whale sounds was distributed to the workshop group to encourage comparison of different localisation techniques and error analysis. The techniques used in this paper, spectrogram cross-correlation and hyperbolae of equal time difference, are effective for obtaining first-order location estimates, and are meant to provide a basis against which the other estimates in this volume can be compared.

2. METHODS

Five ocean-bottom hydrophones (OBH) were deployed in the Bay of Fundy in a face-centred square array about 14 km on a side (Figure 1, see also Desharnais *et al.*, this issue). The average spacing was 13.8 km and the maximum distance between any two OBHs was 20.2 km. Each device was equipped with an omnidirectional (OAS model E-2SD) hydrophone, a 2-GB disk drive, a temperature-regulated quartz crystal clock, and an acoustic burn-wire release. The OBH's recorded 19.41 min data files at a sampling frequency of 1200 Hz, with a 10-s gap between files. The total recording time was 165.6 h over the 167 h deployment time. The hydrophone signal was low-pass filtered (800 Hz cutoff) prior to recording. The data were digitised using a 12-bit A/D converter with ±5 V range.

The hydrophones were calibrated on the DRDC acoustic barge in Bedford Basin, and have nearly constant sensitivity over the 50 to 700 Hz frequency range. One instrument recorded levels lower than expected by approximately 20 dB: the records from later deployments of this unit in the fall of 2002 indicate an intermittent fault in the receiver electronics.

The bottom locations of the OBHs were refined by using an over-the-side hydrophone to detect timing signals from the acoustic pinger on each OBH (Desharnais *et al.*, this issue), in order to account for OBH drift during its descent to the bottom after launch at the surface. The maximum error in clock drift between OBHs was 36 ms and the maximum uncertainty in OBH positions was 12.5 m.

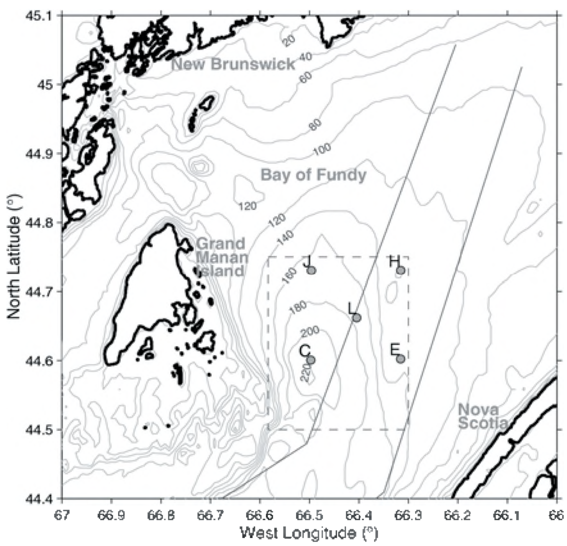

Figure 1. OBH locations in the Bay of Fundy, September 2002.

The data set analysed here consists of a selected set of 15 right whale sounds detected on each of the five hydrophones in the array. Five of these sounds are broadband gunshot-type sounds; the other 10 are tonal-type sounds. The arrival-time-difference between each pair of hydrophones was determined by spectrogram cross-correlation of the logarithmic spectral densities for each sound on the centre OBH against the same sound on the other four OBHs (*e.g.*, Altes 1980, Clark and Ellison 2000). The cross-correlation was performed on a frequency band and time duration manually selected around the sound of interest with 5-Hz frequency resolution and 6-ms time resolution. The intersections of equal-time-difference hyperbolae, for linearly independent time differences among the different hydrophone pairs, then determined the approximate locations of the sound sources. The computations were made assuming constant and spatially uniform sound speed. Sound speed varied between 1490 to 1498 m/s during the time of acoustic sampling (Fig. 2). The variation of RMS location error with sound speed was evaluated at the three sound speed values of 1480, 1485, and 1490 m/s based on preliminary tests of which sound speeds would give more precise hyperbolae intersections.

Localisation error estimates were made using a root-mean-square (RMS) distance ε of the hyperbolae intersections from the mean, $\varepsilon^2 = \varepsilon_x^2 + \varepsilon_y^2$ where ε_x and ε_y are the standard deviations in the zonal and meridional directions respectively.

3. RESULTS

Spectrogram cross-correlation (Fig. 3) and hyperbolae of equal time difference (Fig. 4) produced localisations for all 15 right whale sounds sampled. The seven points of intersection of hyperbolae triples are within about 0.5 km of each other in the example shown (Fig. 5). The average of these points provides the approximate sound source location relative to OBH-L and the standard deviation in the points provides an estimate of the location error. Table 1 lists the relative arrival times of each sound on each OBH.

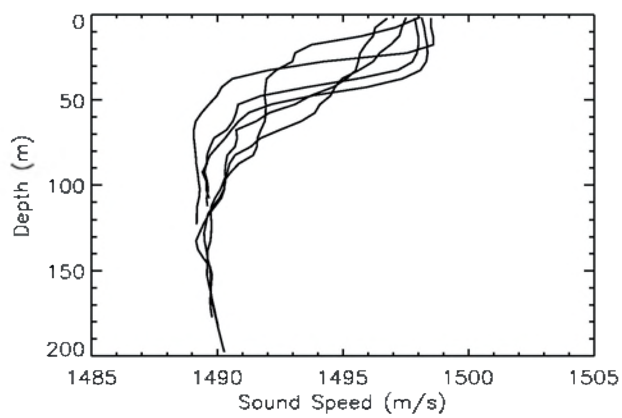

Figure 2. Sound speed profiles from six CTD casts taken near the time of the acoustic data samples.

The locations of the sounds are plotted in Figure 6, together with error bars representing plus or minus one standard deviation. Most of the sound locations are either within or relatively close to the footprint of the array. Two sounds are located about 30 km south of the array centre and, this distance being large compared to the array aperture, are associated with the largest errors.

The smallest RMS localisation error obtained with these data was 0.23 km. Variation of sound speeds for each of the whale sounds affected the localisation precision. Although the average measured sound speed was 1492 m/s, a speed of 1485 m/s gave the best results (smallest overall average RMS error) among the three sound speeds used (Fig. 7). The mean RMS error at 1485 m/s was 0.85 km as compared to 1.10 km and 1.19 km for 1480 m/s and 1490 m/s respectively (Table 2). Speeds greater than 1490 m/s resulted in very poor localisations. The maximum RMS error at 1485 m/s was 5.6 km for one of the distant (~30km away) mid-frequency sounds. The error for the ten tonal-type sounds (1.0 km) was greater than for the five gunshot sounds (0.6 km). The mean range to the sounds from OBH-L was 10 km and the maximum range was 33 km. The locations, error and range of each localised sound are given in Table 3.

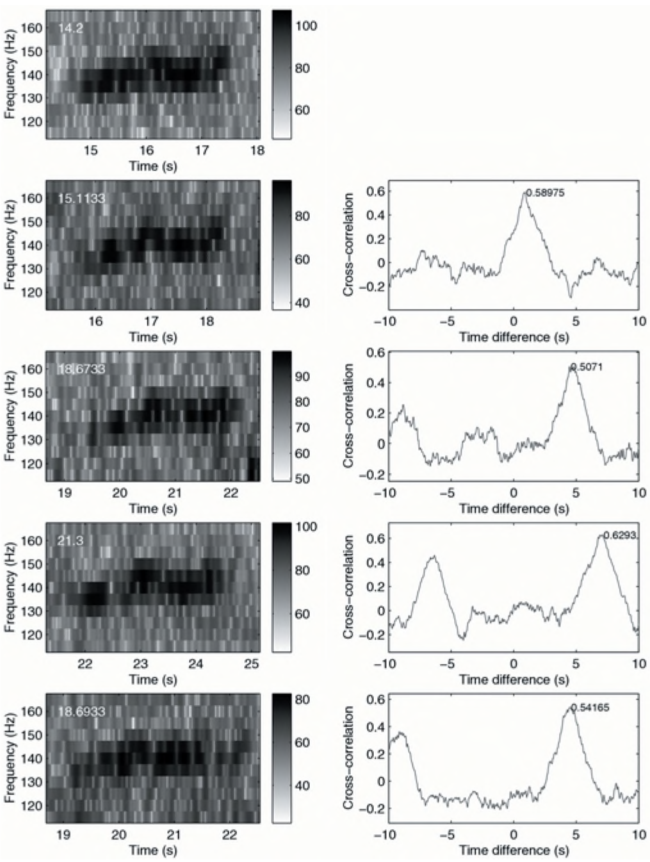

Figure 3. Spectrogram cross-correlation of a tonal sound S-143-8 on OBH-L against OBH-C, E, H, and J respectively. Greyscale in dB re 1 μPa^2/Hz. The relative time difference between the first spectrogram and the other four is estimated from the time of the peak in the cross-correlation function.

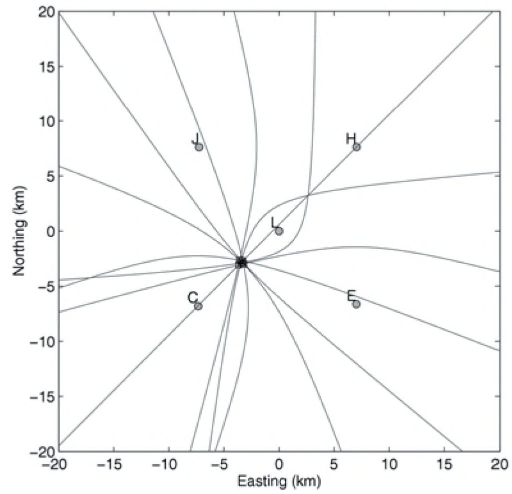

Figure 4. Hyperbolae of equal time difference for S-143-8.

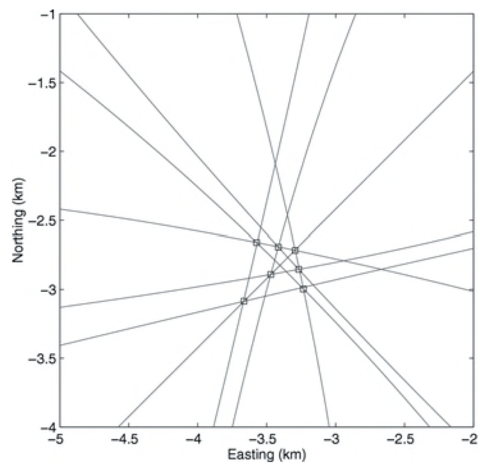

Figure 5. Close-up of localisation in Fig. 3 with squares marking intersections of hyperbolae triples.

Table 1. Relative sound arrival times on each OBH.

Filename	Time (s)				
	OBH-L	OBH-C	OBH-E	OBH-H	OBH-J
S013-1	14.600	13.720	16.000	21.273	20.220
S035-2	14.760	20.527	12.953	14.673	21.247
S070-3	14.680	8.620	18.333	21.500	15.727
S093-4	14.280	20.553	19.520	13.733	15.727
S110-5	14.600	8.813	18.373	21.467	16.107
S092-7	15.400	21.333	20.647	13.227	14.493
S093-9	14.600	17.167	21.347	18.527	10.287
S131-10	15.320	22.320	20.107	17.407	20.227
S131-11	15.400	22.647	19.880	17.487	20.640
S131-12	14.680	21.733	20.273	18.213	19.667
S131-13	14.600	21.773	20.247	17.940	19.720
S134-6	15.320	22.193	21.580	20.020	20.447
S143-8	14.200	15.113	18.673	21.300	18.693
S209-14	14.280	10.907	10.047	19.427	20.153
S210-15	14.600	11.273	10.200	19.740	20.493

Table 2. Average error for the three sound speeds and three types of sounds (gunshot, low-frequency tonal, and mid-frequency tonal). All low-frequency tonals were localised at less than 10 km and mid-frequency tonals at more than 28 km from OBH-L.

	RMS (km)		
Sound speed (m/s)	1480	1485	1490
Gunshots	0.45	0.56	0.89
Low-frequency tonals	0.55	0.39	0.43
Mid-frequency tonals	4.86	3.46	5.00
All tonals	1.41	1.00	1.34
All sounds	1.09	0.85	1.19

Table 3. Position, error, and range of sounds relative to OBH-L, for 1485 m/s sound speed.

Filename	Type	x (km)	ε_x (1 sd)	y (km)	ε_y (1 sd)	RMS (km)	Range (km)
S013-1	G	-1.84	0.03	-6.55	0.06	0.07	6.80
S035-2	G	8.95	0.76	-0.97	0.62	0.98	9.00
S070-3	G	-11.20	0.56	-6.39	0.36	0.66	12.89
S093-4	G	1.32	0.12	6.42	0.22	0.25	6.56
S110-5	G	-9.75	0.71	-5.75	0.44	0.84	11.32
S092-7	LF	0.90	0.18	9.69	0.42	0.46	9.73
S093-9	LF	-6.95	0.49	5.25	0.35	0.60	8.71
S131-10	LF	2.37	0.17	2.86	0.17	0.24	3.72
S131-11	LF	2.83	0.30	2.60	0.29	0.42	3.85
S131-12	LF	1.23	0.23	2.51	0.21	0.31	2.79
S131-13	LF	1.35	0.35	2.58	0.30	0.46	2.91
S134-6	LF	0.18	0.32	2.06	0.22	0.39	2.07
S143-8	LF	-3.42	0.16	-2.84	0.16	0.23	4.45
S209-14	MF	2.64	0.50	-29.10	5.58	5.60	29.22
S210-15	MF	3.16	0.23	-32.94	1.29	1.31	33.09

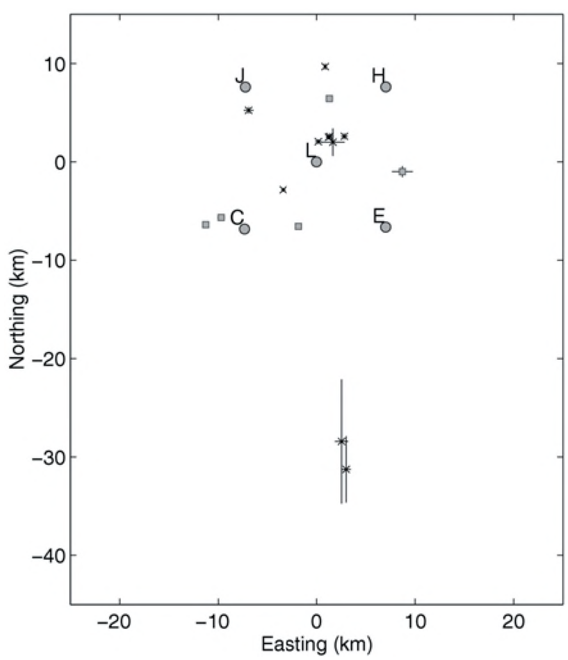

Figure 6. Localised position of each sound with 1 sd error bars. Sound speed = 1485 m/s. Non-gunshots are crosses, and gunshots are squares. Circles represent the OBHs.

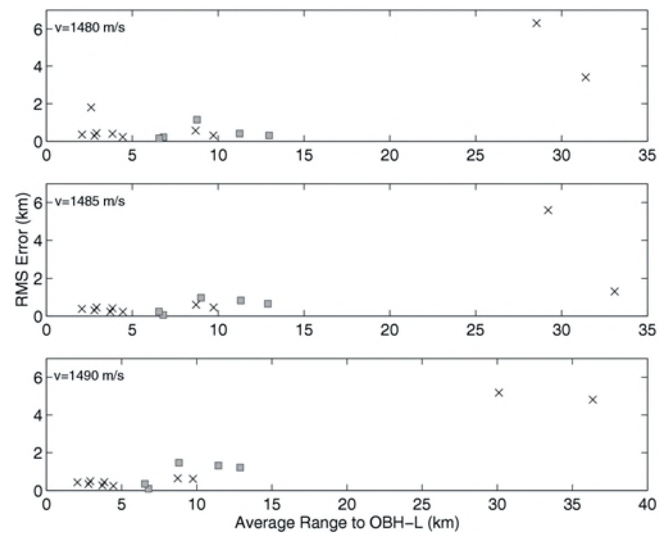

Figure 7. RMS error at three sound speeds. Non-gunshots are crosses, and gunshots are squares.

4. DISCUSSION

The right whale sounds in the Bay of Fundy workshop dataset were localised assuming isovelocity, two-dimensional sound propagation and using spectrogram correlation to determine the arrival time differences. The method yields a relative RMS error, based on the variance among the seven linearly independent location estimates, of 1 km overall (*i.e.* averaged over all 15 sounds). The error for low-frequency tonal sounds and gunshots located at distances less than about 10 km away from the centre of the array is about 0.5 km. The mid-frequency tonal sounds resulted in a much higher error of about 5 km. There were only 2 mid-frequency sounds, both 30-km distant, and the larger error for these sounds is likely due to this distance being larger than the array aperture and not due to the sounds being of higher frequency. Range error increases with distance from the array with the hyperbolic fixing technique.

Errors in arrival-time-differences determined from spectrogram cross-correlations were unlikely to have resulted in significant localisation errors. Time resolution in the spectrograms was 6 ms, so a shift in the cross-correlation peak of 5 samples would result in 50 m error in the localisation. The errors in the OBH timing and positions could have contributed about 70 m error in the localisations. These errors were small compared to the 340 m difference between using 1485 m/s and 1490 m/s sound speed.

The location results of this study can be directly compared to those obtained on the same dataset by Desharnais *et al.* (this issue) and Simons *et al.* (this issue). As with a sonobuoy study in the same area (Laurinolli *et al.* 2003), right whales were localised as far as 30 km and the average localisation distance was 10 km. The smaller location error obtained with a sound speed less than the mean measured speed indicates that direct-path detection is unlikely. The sounds are taking longer to get to the receivers because of multipaths and reflections not because the sound speed is lower than expected. Thus, the location error could likely be reduced by allowing the sound speed profile to vary with time and space, requiring the use of range-dependent ray or modal sound propagation models.

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