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Numbers and Distributions of Bowhead Whales, *Balaena mysticetus*, Based on the 1985 Acoustic Study off Pt. Barrow, Alaska

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ABSTRACT

Acoustic locations were computed for bowhead whale calls recorded on multi- channel tapes made during the whales' spring migration off Point Barrow, Alaska in 1985. Acoustic location analysis was completed on 332 hrs of tapes resulting in 3,368 locations. Locations were converted into tracks and, from these, numbers of vocalizing whales and the distribution of their closest point of approach relative to the visual observation perch were calculated. These data were corrected to take into account the effects of array geometry, distance to a calling whale, whales that swim in pairs, and time periods when calls were recorded but not analyzed. The results indicate that there were 4,008 vocalizing bowheads detected in 1985 during the 909 hrs of acoustic observation. This estimate is further corrected to 5,290 whales when time periods during the migration with no acoustic monitoring are taken into account.

INTRODUCTION

The majority of sounds produced by bowhead whales (*Balaena mysticetus*) have excellent acoustic properties for long-range (>1km) underwater transmission and detection. Their vocalizations are relatively loud, low and frequency-modulated (FM). The acoustic energy is usually restricted to the 100–400Hz band, although they will sometimes produce sounds as low as 50Hz or as high as 4,000Hz (Clark and Johnson, 1984; Ljungblad, Thompson and Moore, 1982; Ljungblad, Moore and Van Schoik, 1984). Calls have been recorded with estimated peak source levels between 129 and 189 dB *re* 1 μPa at 1m (Cummings and Holliday, 1985), although most FM calls are produced at an average estimated source level of 150 ± 9.4 SD dB *re* 1 μPa/100Hz at 1m (Clark, Ellison and Beeman, 1986a). In all studies to date, the most common types of vocalizations have been low (80–300Hz) FM sweeps lasting 0.5–1.5s.

Acoustic census studies, during the spring migration of bowhead whales off Point Barrow (Alaska, USA), were initiated in 1978 (Braham, Krogman, Leatherwood, Marquette, Rugh, Tillman, Johnson and Carroll, 1979) and have continued since then with varying levels of effort and emphasis (e.g. Clark and Johnson, 1984; Cummings and Holliday, 1985; Clark, Ellison and Beeman, 1986b). The original premise for these studies was that acoustic methods could take advantage of the high rates (1–200 calls/hr) of calling and the characteristics of bowhead calls to locate vocalizing whales that were not seen by visual observers. The results from the 1984 season (Clark, Ellison and Beeman, 1986c) demonstrate that acoustic methods can: (1) detect and locate the same whales seen by visual observers; (2) continue to function during periods when the visual observations are ineffective (e.g. poor visibility, no open water etc.); and (3) provide information on the numbers and distributions of whales that are beyond the range of visual detection (*ca* > 2.5–4.0km), independent of visual sighting conditions. Clark *et al.* (1986b) detailed the progress made in analyzing the 1985 data for acoustic locations which, at that time, had not been converted into numbers and distributions of whales. This paper presents the results of the completed acoustic census analysis based solely on the 1985 acoustic data.

METHODS

Field methods and acoustic locations

The major objective of the acoustic field study was to monitor and record the sounds of the whales on linear arrays of 3–4 hydrophones throughout as much of the migration as possible. Later, a representative portion of these acoustic data tapes was analyzed for acoustic locations. These basic field methods, as well as the methods for acoustic location and analysis, are described in Clark *et al.* (1986b). Acoustic analysis began with the conversion of each tape into a continuous stereographic visual display of two audio channels, referred to as a stereogram (see Clark *et al.*, 1986b, Fig. 1). Bowhead calls were identified as to type and time of occurrence from these visual representations of sounds, which then also served as a guide for the computer operator during the sound location process.

The area over which reliable locations are obtained is particularly sensitive to the geometry of the hydrophone array, which is arranged as an approximate line of sensors along the edge of the ice, approximately parallel to the whales' migration path. As a result of this linear arrangement and the method of computing locations by the time-of-arrival technique, a sound source becomes increasingly more difficult to locate as its bearing gets closer to the axis of the array. Knowing this, no attempt was made to locate whale sounds with bearings within 30° of the array axis. However, an attempt was made to locate

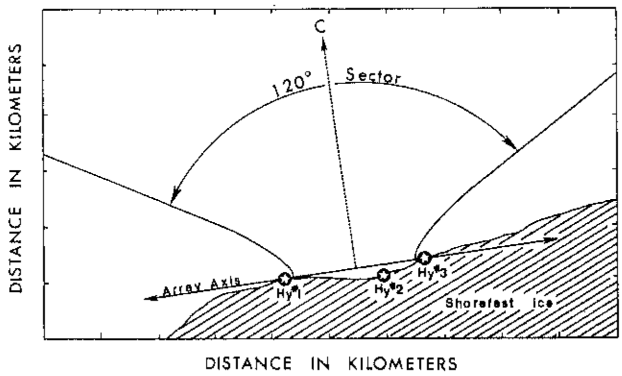

Fig. 1. Diagram of the 120° sector area in which acoustic locations were computed. The axis of the array is the line running through the hydrophones at the ends of the array, while the center of the array is the line, C, perpendicular to the midpoint of the array axis.

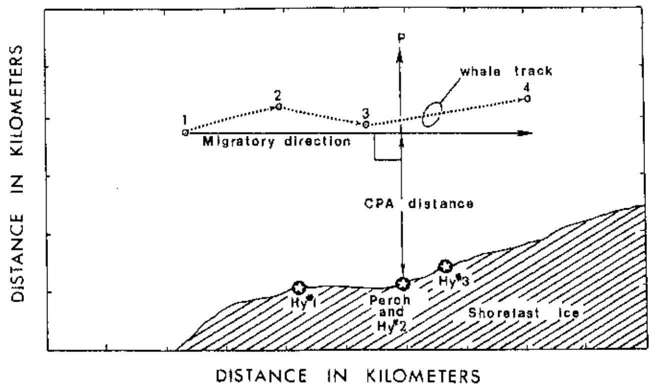

Fig. 2. Diagram of the method for calculating a whale's closest point of approach (CPA) distance from the visual observation perch. The CPA distance is computed by projecting the first whale location in a whale track onto the line, P, originating at the perch and perpendicular to the migratory direction.

every sound that was heard within the 120° sector centered on the midpoint of the array (Fig. 1). It is important to understand that the effects of the array geometry on the sound location method do not disappear abruptly at the edges of the 120° sector, but instead modify the chances of accurately locating a vocalizing whale depending upon where it is within the 120° sector. An appreciation of the geometry and its resultant effect on the efficiency of the acoustic location method is critical to the process of deriving a correction term for those whales that were heard but not located. This is discussed under the 'Correction factors' section below.

In all further discussion the terms sound and call are equivalent and refer to a bowhead vocalization and not to bowhead songs (Ljungblad *et al.*, 1982) which are excluded from all analyses in this report. Counts of bowhead calls refer to the numbers of sounds tallied for some period of time. There are two types of counts referred to here, field counts and measured counts. Field counts are the numbers of calls noted by acoustic observers in the field at the time of monitoring and recording. Measured counts are the numbers of calls found on the tapes as a result of acoustic analysis.

Blocks of time selected for location analysis are referred to as 'segments' (see Zeh, Turet, Gentleman and Raftery, 1987). For each segment all tapes were converted into stereograms and an effort was made to locate every sound with a bearing within the 120° sector. Blocks of time for which acoustic recordings were made but for which location analysis was not performed are referred to as 'non-segments'. Periods of time within the season with similar array and environmental conditions are referred to as 'parts'.

Acoustic tracks and CPA distributions

All sound locations were analyzed for acoustic tracks using the procedures of Sonntag, Ellison, Clark, Corbit and Krogman (1986), while taking into account the various tracking parameters as detailed in Sonntag, Ellison and Corbit (1988). In all acoustic tracking the speed and angle parameters used for the analysis of each segment were identical to those listed in Table 1 of Raftery, Turet and Zeh (1988), and the consolidation parameters were 240s and 150m (T2 and R in Sonntag *et al.*, 1987). An acoustic track is defined as one or more acoustic locations, and it is assumed that there is only one whale per track. Closest point of approach (CPA) distributions, hereafter referred to simply as distributions, were computed by projecting the first location in a track onto the line originating at the visual observation perch and perpendicular to the direction of migration as shown in Fig. 2.

Correction factors

This paper presents the numbers and distributions of whales based solely on acoustic information. These acoustic analyses provide numbers and distributions only for a portion of the actual population passing by the acoustic observation area. The proportion of the vocalizing population counted during the season segments is primarily affected by factors related to spatial and temporal sampling limitations. Spatial sampling limitations affect the proportion of the vocalizing whales that are actually detected and located during an acoustic segment. Temporal sampling limitations affect the proportion of vocalizing whales counted during the periods of acoustic analysis relative to the total duration of the season. In order to take these limitations into account and estimate numbers and distributions of vocalizing whales for the entire migration period, the numbers and distributions computed from the tracking algorithm are corrected for the following:

(a) the acoustic location method does not sample the entire area through which the migration flows with equal certainty (the probability of locating a vocalizing whale as it passes by the array is dependent upon where, relative to that array, the whale makes the sound);
(b) acoustic methods cannot detect two whales in the same track; ie., two or more whales that are swimming so close to each other that their acoustic locations overlap and cannot be unambiguously distinguished;
(c) periods of time when acoustic observations were made but acoustic location analysis was not performed; and
(d) periods of time during the migration when no acoustic observations were made.

Five separate acoustic correction factors are applied to the numbers and distributions of whales computed for each part of the season: (1) the geometric correction; (2) the distance correction; (3) the pairs correction; (4) the non-segment correction; and (5) the not-monitored correction. The order and procedure by which these correction factors are determined is as follows.

Geometric correction factor

A single geometric correction factor is used on all distributions. This factor consists of a set of values that correct for whales that are under-sampled in the 120° sector between 0–5km. The following assumptions are made: (1) the length of time a whale spends in the 120° sector is directly proportional to its distance from the array; (2) whales are swimming at an average speed of 4km/hr; (3) the probability of detecting and locating a vocalizing whale in the 120° sector is directly proportional to the amount of time spent in the sector; and (4) the possibility of locating a whale with a CPA of 5km is 1. The geometric correction factor is defined as the ratio between the time spent within the sector at 5km and the time spent within a sector at some distance less than 5km. The general equation for computing the geometric correction factor for CPA distance m is:

$$\frac{a + v^*c \cos(30)}{a + v^*m \cos(30)} \tag{1}$$

where a is the separation distance between the end hydrophones in the array, (1.6km), v is the average swimming speed (4km/hr) and c is the distance out to which the correction factor is applied, (5km). The use of 5km as the distance out to which this correction is applied is based on the mathematics of the sound location process which shows that, given reliable time delays, the probability of locating a whale within the 120° sector is independent of distance, out to a radius of *ca* 5km. The probability of obtaining a good location beyond 5km is a function of both range and bearing, even if reliable time delays are obtained.

Distance correction factor

For distances greater than 5km it is assumed that no geometric correction factor is necessary. But we know that the ability of the acoustic method to detect and locate a call is a function of the distance between the calling whale and the array. For simplicity, we assume that the range at which this detection problem begins to affect the probability of counting a whale is 10km, and that the probability of locating a vocalizing whale at more than 10km is 0.5. Therefore, the distance correction factor simply multiplies the total number of whales in the distribution that are greater than 10km offshore by a factor of 2. It is important to note that the original number of whales in the 5–10km range is not changed by either the geometric or distance correction factor and that it is assumed we are counting all the whales that pass through the area 5–10km offshore of the array.

Pairs correction factor

The total numbers of whales in the distributions (after correction for geometry and distance) are corrected for the percentage of tracks expected to contain two whales. The pairs correction factor is different for different periods of the season and is determined from visual observation data for those periods. A pairs correction factor of 20%, for example, means that *ca* 20% of all whales seen during that part of the season were travelling within several body lengths of another whale and therefore could not be acoustically distinguished as two whales using the present acoustic methods. The pairs correction factors for 1985 are 5% for the 21 April-17 May period and 10% for the 17 May-7 June period.

Non-segment correction factor

Non-segment correction factors are computed for each part of the season using the following procedure. Numbers of whales from all the segments, after correction by the above three factors, are summed to yield a value representing all the whales detected acoustically during the part. All the calls heard by acoustic observers for all segments and non-segments are compiled from field counts. The total number of calls during all the four-hour periods before and after each segment are also compiled from field counts and added to the number of calls heard during the segments and subtracted from the number of calls heard during the non-segments to yield corrected counts. This procedure of adding back sounds from four-hour periods that are not analyzed but which are contiguous with analyzed segments is a conservative means of reducing the chances of counting a whale twice; once when it is actually located within a segment and once when it is heard during a non-segment. The number of whales during each non-segment period is then estimated by the ratio:

$$\text{non-segment whales} = \text{segment whales} \times \frac{\text{non-segment calls}}{\text{segment calls}} \tag{2}$$

The total number of vocalizing whales estimated for each part of the season is the sum of all non-segment and segment whales.

Not-monitored correction factor

In 1985, from the time the first bowhead call was heard (2200 hrs, 21 April) to the time of the last call (2100 hrs, 10 June), there was a total of 290 hrs (12.1 days) with no monitoring. This lack of monitoring effort was primarily a result of environmental conditions that prevented us from safely deploying and maintaining the acoustic recording equipment. It was not due to a lack of whales. These 290 hrs of time without acoustic monitoring represent 24% of the 1985 acoustic season. To correct for this, the total number of whales from all parts after all other corrections was multiplied by 1.32.

RESULTS

In 1985 acoustic monitoring began on 14 April and ended on 10 June. The first bowhead call was heard on 21 April and a few calls were still heard on 10 June when the acoustic study ceased. For all of 1985, a total of 22,007 bowhead calls was noted by acoustic observers during 909 hrs of acoustic monitoring. There were 811 hrs of tapes recorded when an array was functioning. Location analysis was performed on 332 of the 811 hrs of array recordings. This analysis resulted in 3,368 acoustic locations. Fig. 3 shows a histogram plot of the daily field counts and acoustic monitoring effort for the 1985 season.

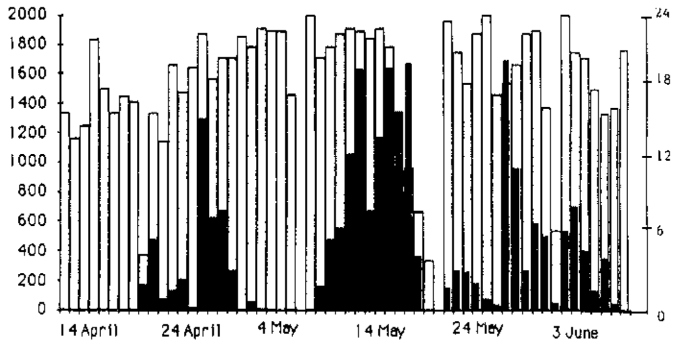

Fig. 3. Daily field counts of bowhead calls (black bars) and numbers of hours of acoustic monitoring (white bars) during the 1985 season.

Table 1

Summary of 1985 acoustic analysis results for all segments uncorrected for any of the correction factors

Date	Perch	Acoustic condition	Hours analyzed	Measured counts	Acoustic locations	Whales located
23 April	Castle	good	24	459	9	5
28 April - 1 May	Castle	excellent	96	3,058	1,421	323
10 May	Flounder	fair	6	24	5	2
11 May	Flounder	poor	8	157	24	14
12 May	Flounder	good	7	64	37	18
13 May	Flounder	fair	14	390	147	60
14 May	Flounder	fair	24	1,745	720	163
15 May	Flounder	good	24	831	244	103
16 May	Flounder	good	24	1,896	458	133
19 May	Slippery	poor	18	1,388	109	61
30 May	Perilous	fair	24	816	36	30
31 May	Perilous	poor	24	269	56	34
1 June	Perilous	poor	10	365	45	24
2 June	Perilous	poor	17	260	12	6
6-7 June	Perilous	poor	12	278	45	28
Total			332	12,000	3,368	1,004

The season was divided into four acoustic analysis parts, referred to as Castle, Flounder, Slippery and Perilous, and named after the visual observation perches and arrays established at different locations during those time periods. The Castle part is from 21 April-7 May. The Flounder part is for 9–17 May and 23–28 May. The Slippery part is for 18–20 May. The Perilous part is for 30 May-10 June. Table 1 gives a breakdown of the acoustic analysis effort and results for the different segments within the four parts.

Table 2

Listing of bowhead whales sound counts and numbers of acoustic whales for each of the four parts of the 1985 season. Field Count is the total field count of calls for that part of the season. Corrected Segment Count is the corrected field count of calls during all the segments in that part of the season. Corrected Non-segment Count is the corrected field count of calls for all the non-segments. Segment Whales is the number of whales after correction by the geometric, distance and pairs correction factors. Non-segment Whales is the number of whales in the non-analyzed part of the season, calculated using equation (2) above. All Whales is the total number of whales for each part of the season

Part	Field count	Corrected segment count	Corrected non-segment count	Segment whales	Non-segment whales	All whales
Castle	4,038	3,505	533	1,088	165	1,253
Flounder	8,342	5,338	3,004	899	506	1,405
Slippery	3,381	1,753	1,628	206	191	397
Perilous	6,246	2,675	3,571	408	545	953
Total	22,007	13,271	8,736	2,601	1,407	4,008

Corrected CPA distributions were computed from the original distributions for each of the four parts using the geometric and distance correction factors. Figs 4–7 show the corrected distributions for the four parts. Fig. 8 shows the original (black bars) and corrected distributions (open bars) for all four parts combined. Table 2 gives a listing of the sound counts and whale counts for each of the four parts of the season.

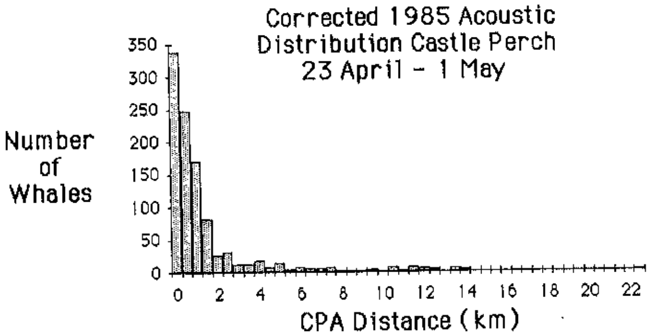

Fig. 4. 1985 CPA distribution corrected by geometric and distance factors; Castle perch, 23 April – 1 May.

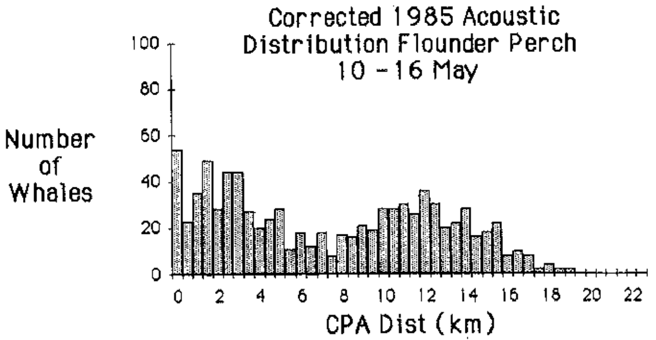

Fig. 5. 1985 CPA distribution corrected by geometric and distance factors; Flounder perch, 10 – 16 May.

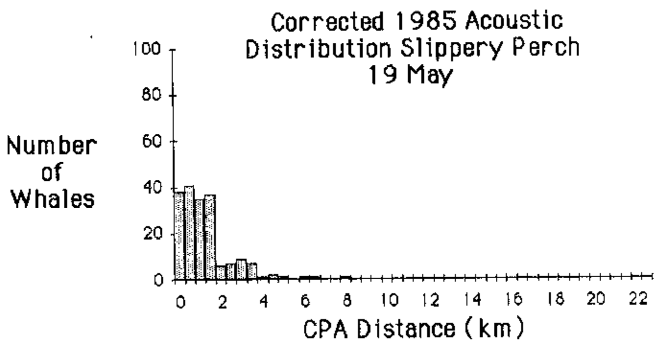

Fig. 6. 1985 CPA distribution corrected by geometric and distance factors; Slippery perch, 19 May.

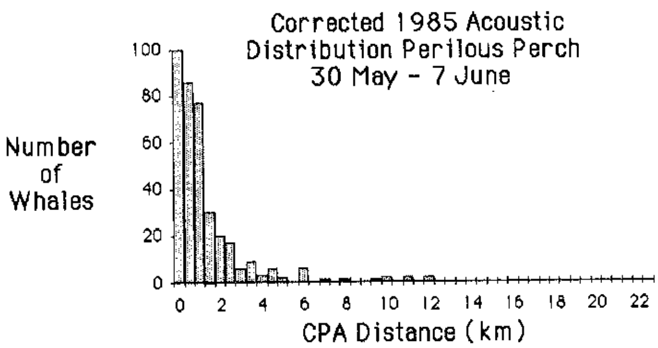

Fig. 7. 1985 CPA distribution corrected by geometric and distance factors; Perilous perch, 30 May – 7 June.

After correction by the geometric, distance and pairs correction factors, there were 1,088 whales during the Castle part, 899 during Flounder, 206 during Slippery and 408 during Perilous (column headed Segment Whales in Table 2). After correction for non-segment sounds heard in the four hours before each segment, the total numbers of

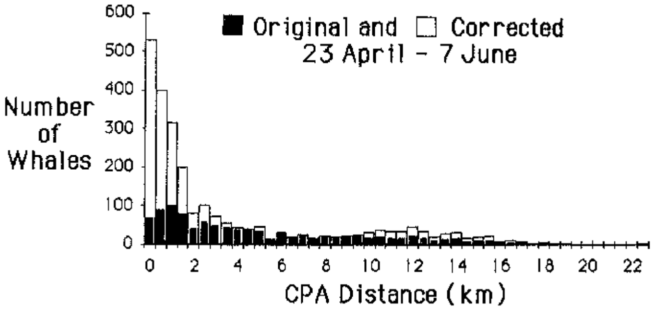

Fig. 8. 1985 CPA distributions, original (black bars) and corrected (white bars) by geometric and distance factors; all four parts of the season combined.

whales in each part are 1,253 (Castle), 1,405 (Flounder), 397 (Slippery), and 953 (Perilous) (column headed All Whales in Table 2), for a total of 4,008 whales. After correction for the 24% of the season during which we were not able to monitor the whales acoustically, the total acoustic estimate for all parts of the 1985 season is 5,290 whales.

DISCUSSION

The estimate of 5,290 for 1985 is a conservative estimate for the numbers of bowhead whales heard vocalizing as they passed through the acoustic observation area. These estimates are conservative for the reasons discussed below.

(1) The method of determining the location of a calling whale does not result in an exact coordinate position, but instead results in a position with associated errors in the range and bearing to the calling whale. We use ±2 standard deviations in the time delay values to compute the largest possible errors associated with a location. This standard deviation value is based upon the results of a calibration experiment (Ellison *et al.*, 1986). As a result of using these larger error values, more acoustic locations are linked into a track during the tracking analysis, which lowers the total number of whales counted.

(2) Parameters used by the tracking program for joining locations into tracks are chosen so as to minimize the number of tracks (see Sonntag *et al.*, 1987).

(3) We have assumed that all sounds heard in the four hours before and after any acoustic analysis period are from whales that were heard and counted in that period. It is probable that many of the sounds heard in these adjacent four hour periods are not from whales counted in that period. We are presently in the process of determining a more appropriate form of correcting for these pre- and post-segment sounds.

(4) In the geometric and distance correction procedures we have assumed that all whales that vocalize in the 5–10km band parallel to the array are located regardless of where they are heard in that band. This is most probably a false assumption, since it is highly unlikely that the acoustic method locates all whales that vocalize 5–10km offshore. Certainly this is not a true assumption for Slippery perch where high noise levels made it extremely difficult even todetect calling whales that were 5–10km away. Ambient noise levels provide a means of helping to quantify the detection probability as a function of range, and in the future these levels should be used to adjust the distance correction factor in a more realistic and quantitative manner.

(5) Throughout all these analyses, there has been no attempt to correct for different acoustic conditions. At present, our description of acoustic condition is a qualitative index representing the summed effects of ambient noise, reverberation and local phenomena around each hydrophone (ice breaking, waves breaking against an ice wall, etc.). There are indications that the ratio of locations to total sounds for any period differs with acoustic condition. For example, during the 96 hrs with excellent acoustic conditions at Flounder perch, 47% (1,422 locations, 3,058 calls, 323 whales) of the calls recorded were located, while during the 91 h with poor acoustic conditions at Slippery perch, 10% (246 locations, 2,429 calls, 159 whales) of the possible calls were located. We believe that these differences in the percentages of calls located are simply a result of the effects of the physical acoustic conditions on the acoustic method and are not a result of the whales changing their vocal behavior (i.e. calling more often) under conditions that we define as poor. The poor conditions in this case were due to having the array installed along a deep wall of ice which caused signals to be highly reverberant, and to the swift water currents which resulted in high levels of flow noise around the hydrophones.

In 1985, 57% of the 1,004 whales detected acoustically, before correction for geometry and distance (see Fig. 8), were > 3km offshore of the array. After correction for geometry and distance, this percentage decreased to 34%. Thus, even with a substantial correction within the 3km nearshore zone, a third of the vocalizing whales were not within range of the visual observers.

It is clear from Figs. 4–8 that the numbers and distributions of whales throughout the season are not constant but vary considerably over periods lasting hours to days. This variability is due to both real differences and differences introduced as a result of not being able to obtain good multi-channel recordings needed for the location analysis. For example, on 19 May at Slippery perch, recording conditions were poor because the array was installed along the edge of a 7–10m underwater wall of ice which caused considerable levels of acoustic reflection, and because there was a strong 3–4 knot current causing a high level of flow noise at the hydrophones. The effect of these poor conditions was to severely limit the chances of even detecting a whale vocalizing more than 5km from the array as well as to limit the chances of locating a whale that was closer than 5km from the array. We know from visual observation data (Zeh *et al.*, 1988) that this was one of the periods of greatest nearshore whale passage, and we know from acoustic monitoring data that acoustic activity was very high. In this case, it is clear that the acoustic location method was not very efficient in locating most of the whales, and from this we reason that the acoustic analysis results for this period (see Fig. 6) are not representative of the actual number and distribution of whales. In another case the resultant difference between distributions for different parts of the season is most probably real. For example, the 23 April-1 May period was characterized by excellent recording conditions; there were low levels of ambient noise and reverberation, little ice movement and little current. A calibration (Ellison, Clark and Beeman, 1986) experiment out to 5km showed that under excellent signal to noise conditions the error in the location system was 2–3% of the range. Because the location analysis process was not subject to errors introduced by poor recording conditions, we believe that the distribution as shown in Fig. 4 is quite accurate and that indeed most of the whales (86%) were within 3km of the visual observation perch. This distribution is quite different from that for the 10–16 May period (Fig. 5) when conditions were mostly fair to good and 73% of the whales, even after correction by the geometric and distance correction factors, were more than 3km offshore.

The primary aspect of the above procedures which needs further work is support for the various assumptions used to derive the correction factors. In the analysis presented here, the geometric correction factor accounts for the greatest increase in acoustic estimates and is based upon assumptions concerning rates of vocalization and swimming speeds. The distance correction factor simply assumes that we locate half of all whales that pass > 10km from the array. What is needed is a probability function which adequately describes the likelihood of locating a whale as a function of range and bearing from the array and ambient noise conditions. This function would subsume the geometric and distance correction factors and more accurately reflect the actual probabilities of locating a whale over the course of the season. This function can be derived using both theoretical methods and empirical data. The theoretical method would involve the physical constraints imposed by the process for computing time delays, the size of the array and the ambient noise conditions. The complementary empirical method would require analyzing location and track statistics as a function of range and bearing, and computing bearings to all vocalizations, not just those in the 120° sector. These data would provide information on inter-call time intervals; information which is critical for deriving statistics on the probability of a whale vocalizing during any particular time period. By proceeding along these lines, it might eventually be possible to compute numbers and distributions of vocalizing animals using only the bearing information. The acoustic analysis process would then become simpler, proceed at a much faster pace, and become more automated. The correction methods would be derived from known physical constraints on the methods and measured characteristics of the whales' vocal behavior throughout the field season.

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