THE USE OF BOWHEAD VOCALIZATIONS TO AUGMENT VISUAL CENSUSING ESTIMATES ON THE NUMBER OF WHALES MIGRATING OFF BARROW, ALASKA IN THE SPRING OF 1980

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NOTE

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The opinions, findings, conclusions and recommendations expressed in this report are those of the author only and do not necessarily reflect the views of the North Slope Borough

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Abstract

Bowhead whale sounds were monitored and recorded in close coordination with the visual censusing effort during the 1980 spring migration off Barrow, Alaska. Analyses of the acoustic data has resulted in an improvement in the estimate of the migrating bowhead population from the original value of 1945 whales, based solely on visual sightings during good to excellent conditions, to a higher estimate of between 2652 and 3004 animals calculated by incorporating acoustic information into the estimating procedure. The value of this method was dependent on the demonstration of a significant correlation between sounds heard and whales seen as well as on empirical values for signal intensities at various distances from the hydrophone array. The results are encouraging and demonstrate that acoustic censusing methods can be effectively used in conjunction with visual censusing procedures to augment the resulting population estimates.
INTRODUCTION

Ever since the initial days of recording whale sounds it has been suggested that acoustic methods could help determine the presence and number of whales in a given area. A number of researchers, for example, Kibblewhite, Denham and Barnes (1967), Patterson and Hamilton (1964) and Walker (1963), have detected and in some cases even tracked unseen whales using acoustic techniques. Winn, Edel and Taruski (1975) used a dipole hydrophone system to acoustically estimate the number of humpbacks, *Megaptera novaeangliae*, in the West Indies. Their acoustic counts were consistently lower than the counts estimated from visual sightings. For southern right whales, *Eubalaena australis*, it has been shown that there are significant correlations between the number of whales within the Golfo San Jose and the number of low-frequency-modulated calls produced (Clark and Clark, 1981). In bowheads, *Balaena mysticetus*, associations between activities and acoustic behavior are just now beginning to emerge from the studies conducted on the summer feeding grounds in the Eastern Beaufort Sea (Würsig, Clark, Dorsey, Fraker and Payne, 1982).

Thus, there are situations in which associations between visual and acoustic observations have yielded important results. However, with respect to the specific idea of censusing a population using acoustical techniques, there are few empirical data that have really demonstrated the accuracy of the method.

The major obstacle to presenting a convincing argument in favor of acoustic censusing is in the difficulty of ever really knowing how many whales were responsible for the sounds. That is, there must be some basis for defining the relationship between the number of sounds and the number of animals. Without such an association it is difficult to use acoustic data as a means of making confident statements concerning numbers of whales.

This report presents and discusses the results of an acoustic monitoring study conducted in the spring of 1980 off Barrow, Alaska as part of the National Marine Fisheries Service (NMFS) Bowhead Whale Research Project (see Johnson, Braham, Krogman, Marquette, Sonntag and Rugh, 1981, for details). There were four principle objectives to the data reduction; (1) to determine if there was a significant correlation between numbers of whales seen and whale sounds heard, (2) to determine the range of sound intensities produced by an individual whale, (3) to estimate transmission losses as a function of distance from the hydrophones and (4) to plot the distribution of sound intensities in a 90° sector centered on a line perpendicular to the edge of the lead as a function of distance from the hydrophone. The results of these analyses (Clark, 1983b) indicate that:

1. There is a significant correlation between the number of whales seen and the number of whale calls heard;
2. There were 129 whales that were not seen by observers due to fair to poor visibility conditions; and
3. There were approximately 707 to 1,059 whales that passed-by the visual perches unnoticed with the majority of these being out beyond the visual observation range of 2 km.

MATERIALS AND METHODS

The acoustic system consisted of a matched pair of calibrated AQ-17 hydrophones with pre-amplifiers, a Nagra IV-S stereo tape recorder (3 3/4 ips) and a real-time underwater sound direction finding device (see Clark 1980 for details). The recording system was flat ± 3 dB from 20 Hz to 10 kHz and the direction finding system was sensitive in the 50 Hz to 500 Hz range with an accuracy of ± 6° to ± 12°. The hydrophone pair was mounted 1.3 m apart on a steel pipe suspended 6 m below the surface at the edge of the lead where water depths were ca. 12 m. All equipment other than the hydrophone array was maintained in a three-walled tent pitched on the ice within 50 m of the lead and the north perch observers.

Continuous acoustic monitoring began on 21 May at 2200 hrs and ended on 29 May at 1200 hrs. During this time period 95% of the visual counts were taken. Throughout this continuous monitoring session, all bowhead sounds were noted per fifteen minute interval by a field observer (Jim H. Johnson or Christopher W. Clark). Stereo recordings were also taken opportunistically between 22 May and 29 May for a total of 18.7 hrs of recordings. These stereo recordings served as the basis for later laboratory analysis of bearings to and intensities of bowhead sounds.

All sound recordings were analysed using a Spectral Dynamics real time spectrum analyser SD301C with SD302C ensemble averager. Continuous spectrograms were produced following the procedures discussed by Hopkins, Rossetto and Lutjen (1974). After the continuous spectrograms were produced, each tape was re-listened to again at the same time as the spectral image was scrutinized. During this procedure, each bowhead call on the tape was noted. The call counts for each tape were then compared to the call counts noted during the same fifteen minute period in the field. Regression analysis was done for these pairs of counts with the lab count as the independent variable. This analysis revealed that although field counts were consistently lower than lab counts, the correlations between the pairs were highly significant for both observers (JHJ $r_{xy} = 0.61$, $n = 82$; CWC $r_{xy} = 0.73$, $n = 79$).

All further sound analysis was aimed at determining the bearings to as many sounds on the 18.7 hrs of tapes as possible and the received intensities for those sounds coming from a direction ± 45° on either side of center (where center is an imaginary line perpendicular to the lead and bisecting the hydrophone array). To simplify the procedure, analysis was restricted to only those sounds that were simple, frequency-modulated (FM) calls between 50 and 300 Hz (see Fig. 1). By including only the low FM calls, interference from bearded seal song was eliminated. Also these types of sounds were consistently the most intense and have been shown to serve as long distance contact calls for the closely related southern
Figure 1. Example of low, frequency-modulated bowhead whale call. Frequency range 0-200 Hz. Effective filter bandwidth 45 Hz.
right whale (Clark, 1983, 1983b). These calls were also the most common type of sound recorded in both 1979 and 1980.

In the laboratory, bearings were determined for 5,841 low FM calls by replaying the tape recordings into the sound direction finder. The received intensities for all sounds with bearings within ± 45° of center (n = 1100) were then computed using the real time spectrum analyzer. By considering only those sounds that came from less than 45° on either side of center, the analysis includes the area where bearing accuracy was greatest and excludes the areas where accuracy was poor.

In an attempt to gain some empirical feeling for the variation in signal levels from an individual animal, the data were gleaned for the few unambiguous cases when whales were both visibly and acoustically tracked. These cases also provide data on the relationship between received signal levels and the distance the animal was from the hydrophones.

RESULTS

The Correlation Between Visual Counts and Acoustic Counts: Figure 2 illustrates the data for the numbers of whales seen and the corresponding number of whale sounds heard for 161 of the possible 171 hours of data collecting time between 0900 hrs, 22 May and 1200 hrs 29 May 1980. Ten hours were missed near the end of the study when hazardous conditions forced us to move our equipment from the northern to the southern visual observation site. There is a significant correlation (p < 0.01, r_{xy} = 0.74, n = 161) between these visual and acoustic counts.

During the field work, there were several occasions when visibility conditions worsened quite rapidly, usually due to fog or snow. For the visual observers there was a dramatic drop in whale sightings, while for the acoustic observers there was no concurrent drop in the number of sounds heard. A case in point is indicated on Fig. 2 (underlined portion) between the hours of 0540 and 1500 on the 26 of May, a time period of fair to poor viewing conditions bracketed by periods of excellent and good conditions. It is interesting to note the pulse of visual sightings in the middle of the period of poor visibility. This corresponds to a 71 minute window with very good viewing conditions.

An illustration of the visual and acoustic counts under the two extreme conditions, fair to poor and excellent, is shown in Fig. 3. This figure demonstrates the pronounced difference between whale sightings under these two conditions. In order to estimate the number of whales missed by observers due to such viewing effects, regression analysis was done for the visual and acoustic data collected under each of the four visibility conditions. These results are illustrated in Figure 4 and show that there is no correlation between sounds and whale sightings during fair to poor conditions. An estimate of whales missed during these periods was made by using the number of sounds heard and the regression equation derived from the data for the periods of excellent, very good and good conditions (b_1 = 0.18, r_{xy} = 0.77, n = 148). This calculation predicts
Figure 2. Histogram plots showing the number of whales seen and the number of whale calls heard per hour during the 161 hour period of simultaneous visual and acoustic observations off Point Barrow, Alaska in May 1980.
Figure 3. Plot of visual count and acoustic count pairs for the two extreme visibility conditions, fair to poor and excellent. These values represent counts for simultaneous one hour periods (fair to poor, n = 13; excellent, n = 38) and are plotted as square roots of the counts. The two dashed lines represent the linear regression lines for the two conditions (see Fig. 4 for slopes of these lines).
Figure 4. Regression coefficients for the four different viewing conditions. Number of whales seen per hour was considered the independent variable and number of whale calls heard the dependent variable.
that 129 whales passed by unseen during the 13 hours of fair to poor visibility. 95% confidence limits were -29 and +23 whales. It is important to note that this estimate of 129±23 is based simply on the assumption that during period of good or better conditions the observers were seeing all the whales in the lead. In a later result, I will show that this assumption is not entirely correct and that, in fact, observers were seeing roughly 70% of the whales. If we apply this 70% criterion to the 129±23 estimate, then it is predicted that 184±27 whales passed unseen during the periods of fair to poor visibility.

Distribution of Signal Bearings: There was a surprising result with respect to the distribution of source bearings. During the course of the monitoring session at two different array locations, both acoustic observers became aware of the face that the majority of sounds were coming from the left, that is, from a southerly direction looking down toward the oncoming migration. Later analysis confirmed this sensation. The resultant distribution of bearings for 5,841 sounds (see Fig. 5) shows that 60% of all the low FM calls analysed came from the left, while only approximately 30% came from the 90° center sector. A logical explanation for this observed phenomenon is not obvious.

Transmission Loss and Signal Intensity: In order to determine the relationship between signal intensity and distance, the data were scrutinized for unambiguous cases when a whale was both visually and acoustically tracked. In these cases, the visual tracks were used to interpolate the distance of the whale from the hydrophones for those times when the whale produced a low FM call, and it was in the 90° sector. These data, representing 11 individuals are plotted in Figure 6. These results have two important implications; that the average maximum difference between calls from a whale was around 4 dB (3.8 ± S.D. 1.0 dB), and that at a distance of 2000 m the received levels were about 134 dB/1 μPA), while at 3000 m the levels were 132 dB. It appears, then, that for animals at distances of greater than 2000 m, signal intensities fall off at about 3-4 dB per doubling of distance. This would correspond to the following transmission loss equation for distances of greater than two km;

\[ TL = 10 \times \log r + 1 \text{ dB/km} \quad \text{(this is interpreted as cylindrical spreading)} \]

These two conclusions, that whales do not vary the intensities of their low FM calls by more than 4 dB and that transmission losses at distances of greater than two km appear to follow the 10*log r equation, are acceptable as long as one assumes that whales do not vary the intensity of their calls as a function of their position in the lead and that all eleven individuals produced sounds of the same source intensities.

Distribution of Signal Intensities: A histogram plot of the number of occurrences of particular received signal intensities is shown in Figure 7 (note that the intensity scale is the same as that for Fig. 6). In this intensity distribution plot, there is a monotonic increase in the number of calls starting at 156 dB and going to 132 dB corresponding to distances
Figure 5. Percentage of low, FM calls heard as a function of sound bearing (n = 5841). The ordinate in this schematic represents the line connecting the two visual perches. The center of all sectors represents the center of the hydrophone array.
Figure 6. Received sound intensities versus distance from the hydrophones. Each ellipse encloses the sounds from the same whale. Decibel levels referenced to 1 μPa.

Figure 7. Histogram distribution of received sound intensities for the 1100 calls produced by whales at bearings of less than 45° on either side of the line perpendicular to the axis of the hydrophone array and the nearshore edge of the lead.
starting at 250 m and going to 3000 m. There is a peak in the distribution between 132 and 129 dB followed by a slight plateau from 129 to 120 dB and then a drop to 114 dB. Although signals with intensities of less than 120 dB were detectable, their intensities could not be accurately determined.

The derivation and utilization of a transmission loss equation is not critical to any further discussion. Instead, it is of greater importance to know the value of signal intensity with some confidence limits at distances of two km and three km. These distances represent break points in all following results and discussions which are based upon the percentages of sounds that came from whales inside of the two km and three km radii from the hydrophones. It has already been shown that numbers of sounds and numbers of sightings are significantly correlated and the reasonable assumption has been made that the probability of a whale vocalizing is independent of its position in the lead. Therefore, it follows that the percentages of sounds heard inside and outside two km and three km should be equal to the percentages of whales seen swimming inside and outside two km and three km, respectively.

These percentages are readily derived from the data already presented. The difficulty is having some means of saying how many whales are responsible for how many sounds. From the data available in this study such a value cannot be reliably calculated. However, a conservative figure can be used based on the assumption that the observers saw 100% of the whales that passed within two km (or three km, if that is the break point) of the perches. Using this assumption and the visual and acoustic count distributions as a function of distance, estimates as to the actual number of whales that passed can be calculated. Under the assumption that observers were 100% efficient in their sightings for a particular distance, any increase in the estimate over the visual count of 1945 whales seen represents whales that passed outside of that distance but were not seen during excellent to good viewing conditions (B. Krogman and R. Sonntag, pers. comm.).

First, the visual distribution for whales seen during excellent to good conditions (see Johnson et al. 1981) is transformed from the cartesian to polar coordinate system. This transformation is necessary for two reasons. First acoustic data are presented in terms of distance from a point receiver, while visual data are presented in terms of distance from the edge of the nearshore ice. Second, the time spent by a whale in the 90° center sector is dependent upon how far from the receiver that animal is. The transform rescales the visual data so that both distributions are in the polar coordinate system and corrects for differences in time spent in the sector as a function of distance. The results of the transform are shown in Figure 8. It shows, for example, that 40% of the visual sightings would pass through the 90° sector of two km radius as depicted schematically in Figure 9.

From the acoustic distribution plotted in Figure 7, a table showing percentages of sounds produced inside the two km and three km radii can
Figure 8. The percentages of whales (left-hand histograms) seen within 2 km and 3 km of the nearshore edge of the lead and the percentages of whales (right-hand histograms) seen within a radius of 2 km and 3 km from the hydrophone array. The values in the left-hand histograms are taken from the 1980 visual censusing data during excellent to good viewing conditions. These values were transformed (cartesian to polar) to derive the values presented in the right-hand histograms.
Figure 9. Schematic diagram showing the 90° sector centered on the hydrophone array and the imaginary line bisecting the array and perpendicular to the edge of the nearshore lead. This is the sector in which the array had the greatest accuracy.
be calculated. Table 1 shows these values computed for three different intensity values at each of the two distances, two km and three km. For example, at two km a percentage has been calculated assuming that 135 dB is the intensity of a sound at two km and 138 dB and 132 dB are the confidence limits. These low and high values are included in order to express the uncertainty in estimates of number of whales heard at the various distances.

Table 1 presents the percentages of sounds heard (see Figure 7) and the percentages of whales seen within two radial distances, two km and three km (B. Krogman and R. Sonntag, pers. comm.) of the hydrophone array. A comparison of these acoustic and visual values shows that the percentage of sounds heard within two km or three km is less than the percentage of visual sightings within those distances, suggesting that the visual count underestimates the number of whales actually passing by beyond these two distances.

A measure of this underestimate can be calculated, first by assuming that the inside count for a particular distance is absolutely correct and next by assuming that the inside visual count is only 90% correct.

The first calculation is made using the following equation:

\[
\text{Total whales} = 1945 \times \frac{\% \text{ inside visual count}}{\% \text{ inside acoustic count}}
\]

Table 2 shows the results of these first calculations.

The second calculation is computed using the following equation:

\[
\text{Total whales} = 1945 \times \frac{\% \text{ inside visual count}/0.9}{\% \text{ inside acoustic count}}
\]

Table 3 shows the results of these second calculations.

These equations use the value of 1945 whales, which is the number of animals seen during good to excellent viewing conditions in 1980. Multiplying this count by the \% inside two or three km (visual count) represents the actual number of whales seen inside two or three km. Since there is a significant correlation between whales seen and whales heard, the \% inside (acoustic count) multiplied by the total whales (unknown) should equal the number of animals seen inside. Under the assumption that the inside visual count is only 90% correct, the number of animals seen inside is increased by dividing the count by 0.9.

All these results raise the estimate of number of whales migrating past Point Barrow in 1980. These estimates range from a low of 1,809 to a high of 4,670 whales, not including whales missed due to fair to poor conditions. If whales missed due to poor viewing conditions are added, the result is 1,952 to 4,886 whales. These figures represent the extremes in the estimates. A restricted estimate would consider the middle values at two km (see Tables 2 and 3) of 2,509 and 2,788 plus the value of 184±32 due to poor visibility. This would place the estimate between 2,652 and 3,700 (see Table 4).
Table 1. Percentages of sounds heard within 2 km and 3 km of the hydrophone array for three different values of signal intensity at those distances. The percentages of whales seen within 2 km and 3 km were computed by transforming the visual census data, given as a distribution of sighting distances relative to closest point of approach (CPA), from cartesian to polar values.

<table>
<thead>
<tr>
<th>Radial Distance</th>
<th>Percentages of Sounds Heard Within that Radial Distance</th>
<th>Percentage of Whales seen Within that Radial Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>Middle</td>
</tr>
<tr>
<td>2 km</td>
<td>20%</td>
<td>31%</td>
</tr>
<tr>
<td>(138,135,132 dB)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 km</td>
<td>31%</td>
<td>43%</td>
</tr>
<tr>
<td>(138,135,132 dB)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Estimates of total whales migrating off Barrow, Alaska derived by using acoustic data and visual sighting data and assuming that 100% of all whales swimming within either 2 km or 3 km of the nearshore edge were seen by observers (see text for further explanation).

<table>
<thead>
<tr>
<th>Distance</th>
<th>Total Whales</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
</tr>
<tr>
<td>2 km</td>
<td>1809</td>
</tr>
<tr>
<td>3 km</td>
<td>2208</td>
</tr>
</tbody>
</table>
Table 3. Estimates of total whales migrating off Barrow, Alaska derived by using acoustic data and visual sighting data and assuming that 90% of all whales swimming within either 2 km or 3 km of the nearshore edge were seen by observers (see text for further explanation).

<table>
<thead>
<tr>
<th>Distance</th>
<th>Total Whales</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>Mid</td>
<td>High</td>
</tr>
<tr>
<td>2 km</td>
<td>2010</td>
<td>2788</td>
<td>4322</td>
</tr>
<tr>
<td>3 km</td>
<td>2453</td>
<td>3367</td>
<td>4670</td>
</tr>
</tbody>
</table>

Table 4. Estimates of total whales migrating off Barrow, Alaska derived by using the middle values for 2 km shown in Tables 2 and 3 and adding $184_{-32}^{+41}$, the estimate of whales not seen due to fair to poor visibility.

<table>
<thead>
<tr>
<th></th>
<th>100%</th>
<th>90%</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 km</td>
<td>2725</td>
<td>3004</td>
</tr>
<tr>
<td>2693</td>
<td>2972</td>
<td></td>
</tr>
<tr>
<td>2652</td>
<td>2931</td>
<td></td>
</tr>
</tbody>
</table>
These values are not extreme but could be considered conservative considering that they include a worst case of only 10% error in the visual count inside the two km range.

The estimate range of 2,652 to 3,004, if compared to the original visual count value of 1,945, indicates that the counters saw only between 65% and 73% of the whales that actually passed. The above estimates, calculated by incorporating acoustic data with the visual data, are in close agreement with other estimates for the 1978, 1981 and 1982 seasons (Krogman et al. 1983).

SUMMARY

The integration of simultaneously recorded acoustic and visual data has resulted in an improvement in the estimate of the number of bowhead whales migrating off Barrow, Alaska in May 1980. The use of acoustic data was dependent on the significant correlation between the number of whales seen and the number of whale sounds heard. Once this correlation was established, the distribution of whales seen was compared to the distribution of whale sounds recorded as a function of distance from the observation site. The number of uncounted animals that passed the observers was calculated using the visual count of 1,945 whales seen during excellent to good conditions and assuming that observers saw either 100% or 90% of all whales passing within two km or three km of shore. This results in an estimate of between 707 and 1,059 whales that were not seen by visual observers. This increases the count estimate from 1,945 whales to between 2,652 and 3,004 whales in 1980.

ACKNOWLEDGEMENTS

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