ACOUSTIC TRACKING OF MIGRATING BOWHEAD WHALES

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ABSTRACT

An acoustic study was conducted off Point Barrow, Alaska in the springs of 1984 and 1985 on the bowhead whale, Balaena mysticetus, during their annual migration. Multi-channel tape recordings were made using arrays of sonobuoys, and whales were acoustically located using a customize hardware and software system specifically designed for performing sophisticated signal analyses. The system was field calibrated out to a distance of 4.5 km. The mean error in range to the source was 2.5%, while the mean error in bearing was 0.4 . At present, the acoustic analysis has concentrated on locating and tracking bowheads in order to census the whales and document their acoustic behavior as they move through and under the arctic ice. Results indicate that whales migrate through the area even during very rough ice conditions when visual observers see very few whales, many whales are more than 2.5 km offshore of the visual observation sites, whales that are within 2.5 km of the visual observers are often never seen, and whales use calls to communicate and maintain the cohesion of the herd.

INTRODUCTION

Bowhead whales, Balaena mysticetus, produce extremely loud, low, FM calls which have excellent sound characteristics for long range underwater transmission. The acoustic energy of most calls is restricted to 100-400 Hz, and calls have been recorded with received levels as high as 156 dB re 1 uPa when animals were 100-150 m from the hydrophone (1). Bowheads are also remarkably vocal during their spring migration past Barrow, Alaska. These acoustic characteristics of bowhead calls and their high rates of vocal activity provide an excellent opportunity for locating vocalizing whales by passive acoustic methods.

The technique of locating a sound source at long ranges in the ocean by differences in the sound's time of arrival at an array of hydrophones has had limited success when applied to whales. A four-hydrophone time-of-arrival method has been successfully used by scientists at Woods Hole Oceanographic Institute (WHOI) to track a number of whale species (2). One of us (CWC) has used a three-hydrophone array to track southern right whales, Eubalaena australis (3), and bowhead whales (1). Both these methods have limitations; the WHOI array is quite small (30 m) which limits its effective range to less than 300 m, while the phased array technique is dependent upon visual sightings since it only provides a direction to the source and not its location.

As with the acoustic location method, the method of counting or censusing whales using their vocalizations has also had very limited success. Estimates of the number of singing humpback whales, Megaptera novaeangliae, have been made using a dipole array (4). There have been occasions when significant correlations were found between numbers of whales and numbers of sounds in right whales and bowheads, but these results were entirely dependent upon visual counts of whales. One reason for the lack of success with acoustic cesnsusing is that there is usually no way to link one acoustic location to another. With migrating bowheads this problem is overcome since the whales are swimming in a reasonably well defined direction at a known range of speeds. Thus, linkages between successive sounds are established based upon the statistics of how fast the whales swim in a known direction and by how much this migratory heading can change between successive sightings.

One interesting result of locating and tracking these elusive and poorly understood animals is that suddenly we have a picture of the whales' movements relative to one another plus a timetable of what types of sounds they produce and under what circumstances they produce them. The net result is that by tracking whales acoustically instead of visually we can study their acoustic communication system at a level which was once thought to be impossible.

Here we report on the results from two years of an acoustic study conducted off Point Barrow, Alaska during the spring migration of the bowhead whale (5). We will briefly describe the acoustic location and tracking methods used for detecting and counting whales, and we will present results demonstrating that acoustic techniques are able to detect more whales than visual methods during severe ice conditions and even when visual conditions were considered good or very good. Furthermore, we will show evidence that the whales are using their sounds in order to communicate with other whales so as to coordinate their movements during the migration.

These results have important implications for conservation efforts aimed at determining the present number of bowhead whales in the migrating population as well as our general understanding of how these animals utilize sounds as a means of communicating.

METHODS

The acoustic studies described here were highly integrated with visual censusing studies. For this reason, references will be made throughout this paper to visual observation sites, conditions and data. The term perch refers to the visual observation platform on the ice from which visual data were taken. The term lead refers to an area through which whales might migrate. An open lead is the condition of open water with little to no ice, while a closed lead is the condition when there is no open water and it has traditionally been assumed that whales are not in the area. The visibility terms such as fair or good are based on a visibility categorization system as described by Krogman and Rugh (6). The term visual sighting refers to any visual observation for which the location of a whale was recorded using theodolite techniques (7). The term whale-location refers to the two-dimensional position of the lead as determined using either acoustic location methods or visual sighting methods.

Systems Descriptions: The data acquisition and analysis equipment consists of three systems: 1)a sonobuoy system consisting of an array of three to four sonobuoys for detecting underwater sounds and transmitting that information via radio signals; 2) a receiving and sound recording system consisting of radio receivers to pick up the sonobuoy transmissions, a monitor/amplifier unit, and a multi-channel analog tape recorder; and 3) a computer-based data processing and analysis system for converting the taped analog data into digital data and processing it in order to locate the whale that made the sound.

The sonobuoys used were either modified AN/SSQ-57A's or units from Sippican Ocean Systems, Inc. customizes by Marine Acoustics. In a typical installation the hydrophones are hung over the side of the ice edge or placed in a hole cut through the ice. In general, each hydrophone is placed at the same depth from the surface (10-20 m), typically half the water depth (20-40 m), and one hydrophone of the array (usually the middle phone) is located within 10-50 m of the perch. Each hydrophone is cabled to a transmiter which is mounted on a pole secured at the top of an ice ridge ca. 3-5 m above the water. The receiving and recording equipment are operated in a movable hut located back from the ice edge on the shorefast ice. In the acoustic hut multi-channel tape recordings are made and incoming sounds are monitored on a 24 h basis for as long as at least one sonobuoy remains operational.

Acoustic locations: The computer location analysis system consists of a minicomputer, array processor, graphics terminal, and custom software. This system simultaneously acquires up to four channels of analog input and converts these data into two-dimensional matrices representing the signal in the frequency, amplitude, and time domains. Figure 1 illustrates the same bowhead call as it was received at three different hydrophones.

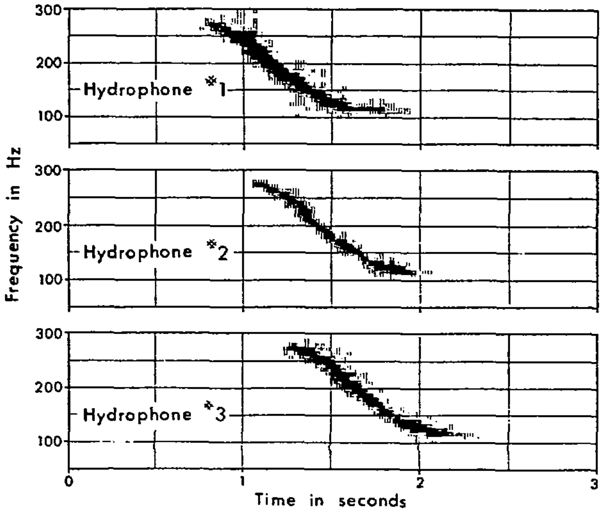

Figure 1. Frequency-amplitude-time plots of the frequency-amplitude-time matrices for the same bowhead whale call as it occurred on three different hydrophones of an array.

This figure clearly shows that the three signals are arriving at different times. In order to precisely compute these differences in arrival times, pairs of matrices are convolved using two-dimensional convolution techniques to compute the time delay between the occurrence of the same sound at each of the hydrophones. This method can be explained using a visual analogy. If the two frequency-amplitude-time matrices are viewed as separate photographicc transparencies, then the time delay between them is found by overlaying the two transparencies and sliding one over the other along the time axis until the two images are optimally aligned. In the actual convolution process the point of optimal alignment is the point of maximum correlation between the two matrices which is equivelent to the time dalay. The location of the sound source (a whale) is based on the fact that the loci of points of equal time delay is a hyperbola. For three hydrophones there are three pairs of hydrophones and therefore three hyperbolic solutions. The common point of intersection of the hyperbolae represents the location of the whale. In most acoustic locations the hyperbolae do not intersect at the same point but instead define a polygon. For three hydrophones the intersections define a triangle. In this case the whale's location is the centroid of the triangle and the size of the triangle is directly proportional to the range and bearing errors associated with that location. Figure 2 is an example of this location process for a three hydrophone array.

Calibration: The primary array calibration involved surveying in the location of each hydrophone using theodolites and infared distance measuring equipment. Speed of sound data were gathered by on site sound velocity measurements and from data available in the literature. The sound velocity profile was essentially independent of depth and was found to be extremely consistent over time and environmental conditions in the months of April and May. For all computations the value for the sound velocity was 1437 m/sec.

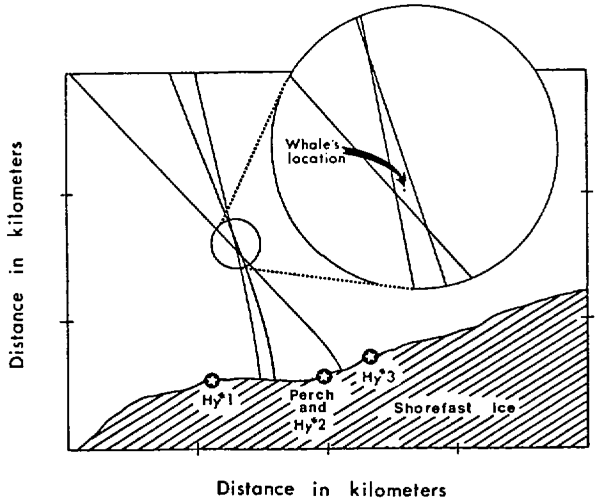

Figure 2. Example of a whale-location derived from the three hyperbolic solutions for three time delays.

For the time delay sound location method, one of the greatest concerns was the lack of adaquate full scale, in situ, validation of the method as applied to locating whale sounds. For this reason a joint acoustic and visual calibration experiment was conducted in 1985 during which a J-11 underwater loudspeaker was used to project synthesized bowhead whale calls from five separate sites, between 925 to 4420 m from the perch, in the exact area through which bowheads were migrating. The "true" position of each broadcast site was determined by taking simultaneous horizontal crossbearings on the site with two theodolites sepatated by 1.4 km. This calibration revealed that the mean errors in bearing and range for the acoustic location method were 0.4 and 2.5%, respectively.

Whale Tracking: All sound locations were analysed for acoustic tracks, and all visual sightings for the same time period were analysed for visual tracks using the procedures of Sonntag et al (1986). Finally all acoustic locations and visual sighting for the same period were combined and analysed for tracks using these same procedures. This tracking procedure links a series of locations into a track based on a range of swimming speeds from 1-8 km/h, a migratory direction of 48 magnetic, and a maximum possible deviation in migratory direction of ± 30 . Once all possible linkages are made the total number of tracks is summed to produce a census count for the period of analysis. A single whale-location that can not be linked to any other location is also considered a track and added to the count. Tracks based only on acoustic locations are referred to as acoustic tracks, those based on visual sightings are referred to as visual tracks, and those based on both acoustic and visual data are referred to as mixed tracks. The final total count from the tracking procedure represents an estimate of the number of whales detected by either acoustic methods, visual methods or both methods, depending on whether the data were acoustic locations, visual sightings, or both data sets combined.

CPA Distributions: Distributions of whales relative to their distance offshore of the visual observation site were made by projecting the first whale-location of a track onto the line originating at the perch and perpendicular to the direction of migration. This distance is referred to as the closest point of approach (CPA) distance and the distribution of all such distances is referred to as the CPA distribution. Figure 3 illustrates this CPA procedure.

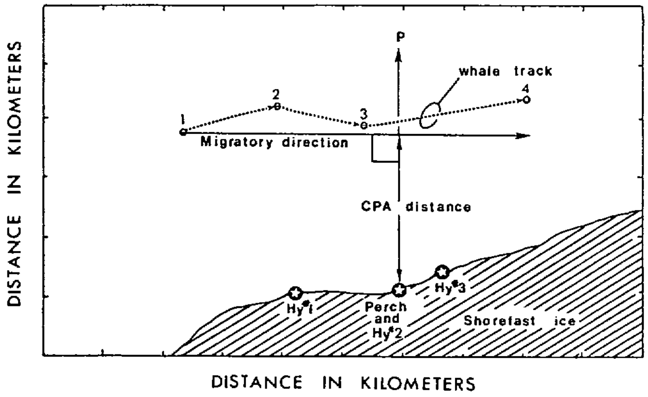

Figure 3. Example of procedure for calculating the closest point of approach (CPA) distance for a single whale track containing four acoustic locations.

For any period of analysis CPA distributions were computed for each of the three data sets; acoustic, visual, and acoustic/visual combined.

A quantitative measure off how many whales were detected and how far away they were from the perch is calculated by adding up all the whales in the CPA distribution. Since this distribution counts each whale only once regardless of how many times it was heard or seen, it is a reliable means of comparing counts based on either of the two observation methods. From the CPA an estimate of how many whales were closer than 2.5 km from the perch is made by adding up all the whales that were within 2.5 km. This 2.5 km value is used because it is the distance to which reliable visual theodolite sightings can be made. In all further discussion whales closer than 2.5 km from the perch are referred to as nearshore whales while whales that are further than 2.5 km are referred to as offshore whales.

RESULTS

In 1984 a total of 196 h of three-channel sound recordings were obtained. From these 89 h were analysed for acoustic locations representing two different time periods. The first period, referred to as Array C-84 included three random sample periods representing 31.5 h of analysis during 3-5 May. The entire Array C-84 was a period of extremely heavy ice conditions (closed lead) when visual observers saw very few whales but high rates of sounds were recorded (range, 0-385; x = 96.8 calls/h). The second period, referred to as Array E-84 and representing 57.5 h of analysis during 18-21 May, was a period when the lead was open, visual observation conditions were good or very good, whales were passing by at moderate rates of 4-6 whales per hour, and moderate rates of bowhead calls were recorded (range, 0-110; x = 34.7 calls/h). This Array E-85 period, during which there were simultaneous acoustic and visual observations, was used as a means of verifying the accuracy and reliability of the acoustic location method. It also represented a visual censusing condition during which visual counts have traditionally been considered accurate. That is, these are conditions for which it has been assumed that almost all the whales within 4 km of the perch are seen by visual observers.

For each of the 1984 array periods all possible sounds were located. This resulted in 600 locations for the Array C-84 period and 356 locations for the Array E-84 period. Each set of locations was analysed for acoustic tracks. For the Array C-84 period there were three whales seen but these were not located with the theodolite, so there were no visual tracks and no mixed tracks for this period. For the Array E-84 period there were 178 visual sightings which were analysed for visual tracks and combined with the acoustic locations for mixed tracks. An example of mixed tracks from Array E-84 is shown in Figure 4.

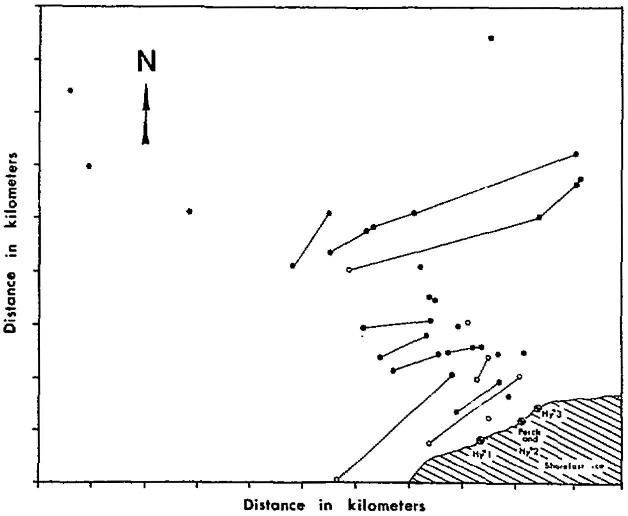

Figure 4. Plot of all whale tracks computed from 33 acoustic locations (closed circles) and 8 visual sightings (open circles) combined for the time period 1349-1615 h on 19 May 1984 during Array E-84 when visual observation conditions were good.

Figure 4 shows a total of 23 whales; 17 were heard but never seen, 2 were both heard and seen, and 4 were seen but not heard. This figure also illustrates the difference in the ranges over which the acoustic and visual methods operate; acoustics routinely locates whales out to distances of 10 km, while visual observers rarely locate whales at 4 km.

The results of the tracking and CPA analysis on all the 1984 data are shown below in tables I and II.

Tables I. Summary of whale counts during Array C-84. The range of values under the column heading 'Total' reflects the fact that 3 whales were seen but never visually located.

	Acoustic Counts	Visual Counts	Total
Offshore	109	0	109
Nearshore	30	3	30-33
Total	139	3	139-142

Table II. Summary of whale counts during Array E-84. Under Combined Counts, 'Acu.' represents whales that were heard but never seen, 'Mix' are whales that were both heard and seen, and 'Vis' are whales that were seen but never heard.

	Acu. Counts	Vis. Counts	Combined Counts Acu.	Mix	Vis.	Total
Offshore	45	7	42	3	4	49
Nearshore	126	89	93	46	54	193
Total	171	96	135	49	58	242

In 1985 a total of 811 h of multi-channel recordings were made for which 386 h were analysed for acoustic locations. Here we will report on a single analysis period lasting four days (96 h) from 28 April through 1 May. This period will be referred to as Array A-85. This period was characterized by fair visual conditions when observers saw moderate numbers of whales, the lead was covered by a thin (8-10") layer of new ice, and moderate rates of bowhead calls were recorded (range, 0-290; x = 36.1 calls/h). This was the same period during which the field calibration was conducted.

For the entire four day period in 1985 all possible sounds were located resulting in 1537 acoustic locations. For this same time period there were 157 visual locations. Only 48 h of these data have been analysed for tracks, and CPA distributions have not been completed. Therefore, only a partial summary of the whale counts for this period is available at this time. These results are given in table III.

Table III. Partial summary of counts of whales for Array A-85 based on 48 h of combined analysis. All visual sightings were within 1 km of the perch.

Combined Counts			
Acoustic	Mixed	Visual	Total
541	29	95	665

DISCUSSION

The importance of the acoustic location method as a censusing tool is obvious when the acoustic results are compared to those from the traditional visual methods. For Array C-84, when the lead was closed, the disparity between acoustic and visual counts is dramatic; Acoustics counted 139 whales compared to the three that were seen. If one is ready to accept that whales migrate under extremely severe ice conditions, then this difference does not seen so extraordinary. However, before these acoustic data were collected and analysed the belief was that whales were not in the area because they couldn't migrate through such conditions. For Array E-84, when the lead was open and visual conditions were good to very good, acoustic methods alone detected nearly twice as many whales as the visual method alone. Even in the nearshore region where it has been assumed that visual methods are efficient, visual observers missed 48% of all the whales that were counted! For the offshore region the inefficacy of the visual method is even more apparent: visual observers missed 86% of all the whales detected offshore. The available data from the 1985 study support the results from 1984. 81% of the total whales detected over a 48 h period in 1985 were never seen by visual observers.

The are two important conclusions to be drawn from the acoustic studies and the comparisons with visual results. The first conclusion is that whales are migrating even under extremely heavy ice conditions when there is no chance of seeing them. The second conclusion is that even under open lead conditions the acoustic method detects more whales than the visual method. What is remarkable is the extent to which acoustic data increases the total number of whales counted. It might be argued that the 1984 and 1985 samples are biased in favor of acoustics because viewing conditions were usually poor or many of the whales were too far away to be seen. But these are exactly the points that need to be stressed; it is probably true that for most years conditions for seeing whales are poor and many whales are too far away to be seen, while conditions for hearing whales are good and they can be reliably located out to 15 km.

These acoustic censusing efforts have not only resulted in improvements in population counts but are now yielding new insights into the whales' system of acoustic communication. When details of tracks are examined in terms of the types of calls produced by individual whales and the timing of the calls, there are occasions when several whales exchange calls with remarkable synchrony. During some of these countercalling episodes all the calls from one whale are identical, while all the calls from the other whale are of another type. An example of two whales countercalling and using individually stereotypic calls is shown in Figure 5. Here we see that one animal always responds to the call of the other animal within a minute of its call. For example, the upper whale makes its third call (an FM upsweep) at 1512:43 and the lower animal, who is almost 2 km away, produces its second call (an FM inflected) at 1513:09. The two distinctive call types used by these two individuals are not vocal signatures, since other whales will produce these same call types. There were also cases of countercalling where one of the whales will switch call types from one that is different from its calling partner to one that is identical. Such plasticity in calling behavior strongly suggests that the whales can control the acoustic characteristics of their calls, and that they are intentionally producing specific call signatures during these vocal exchanges for some purpose. Judging from the synchrony of the call exchanges and swimming tracks a simple explanation is that calling serves the function of keeping individuals in contact and allows members of the migrating herd to coordinate their movements as they migrate through the ice.

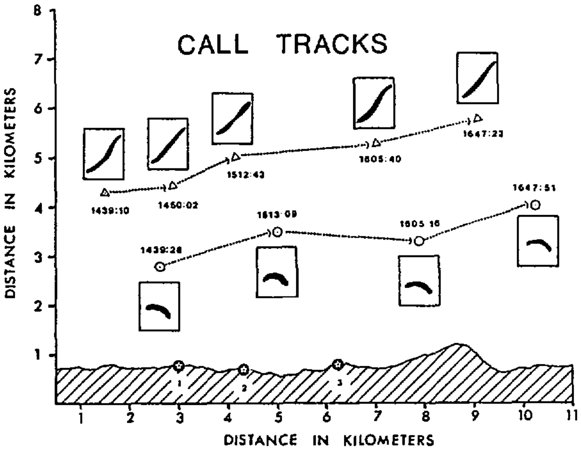

Figure 5. Example of two whales countercalling and using individually distinct call types.

All these results are extremely encouraging. They demonstrate that acoustic techniques can provide us with information on the number of bowheads during a wide range of lead conditions, including closed lead conditions during which it was previously believed by some that no whales were even in the area of Point Barrow. The ability of the acoustic method to count whales under a wide variety of lead conditions and out to distances well beyond the range of visual detection means that the censusing effort can operate effectively for the majority of the two month migratory period. These acoustic results also indicate that the sounds produced by the whales are not arbitrary but actually serve a communicative function. Since call structures are undoubtedly related to the whales' social system and have been influenced by their arctic environment, we should expect that as details of the complexities of their communication system unfold, our understanding of the forces involved in shaping those complexities will improve. Such knowledge will hopefully be used wisely and to the good effect of preserving the unique arctic habitat and its few remaining survivors.

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