Passive acoustic methods applied to fin whale population density estimation

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Assessing the size of cetacean populations in the open ocean has traditionally relied on visual surveys alone. The addition of acoustic monitoring can complement these surveys if reliable protocols can be formulated and calibrated with visual techniques. A study is presented to estimate fin whale population statistics based on near-continuous recording from a single hydrophone. Range to calling animals is estimated by transmission loss and multipath methods to provide a minimum population density estimate. Results are derived from recordings at a hydrophone site north of Oahu, Hawaii that have been the focus of earlier studies. The average calling whale density is 0.027 animals/1000 km^2, while the seasonal maximum calling whale density is about three times the average, or 0.081 animals/1000 km^2. Over 30 fixed hydrophone sites are available around the Worlds Oceans from which such statistics could be generated. © *1999 Acoustical Society of America*. [S0001-4966(99)01005-X]

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INTRODUCTION

Most species of large cetaceans in the open ocean are currently considered endangered and are protected by international agreement. Assessing the viability of marine mammal populations in the pelagic environment requires reliable methods of assessing size, density, and distribution of various population stocks, or at the least relative decline or recovery of a population through time. Both the National Oceanic and Atmospheric Administration, which has responsibility for managing and protecting this resource, and the United States Navy, which operates acoustic and other systems during routine operations, require reliable information on marine mammal stocks in the open ocean. Stock assessment has traditionally relied almost exclusively on visual surveys from surface vessels. Although the technique is well developed and reliable when adequate sampling is available, results suffer in open ocean applications where animal densities are low. Often observations are quite difficult to collect in high-latitude regions during certain times of the year. In addition, the presence of the surface ship carrying the observers can affect the behavior of the animals and influence the results. Underwater acoustics offers a complementary method for assessing cetacean populations that, when combined with other information, can improve population estimates. In many parts of the world's oceans, the seasonality and population density of fin and blue whales are unknown, thus even with significant errors, acoustic surveys are likely to provide a useful contribution. Previous whale acoustic studies have estimated seasonality for fin and blue whales (Clark and Charif, 1998; Moore *et al.*, 1998; Thompson and Friedl, 1982), but have not addressed the potential for minimum or relative population abundance estimation.

Long-duration low-frequency digital recordings are potentially available from more than 30 deep ocean hydrophones deployed around the world's oceans by the U.S. military. These hydrophone systems were designed either to track Soviet submarines or monitor missile impacts and nuclear tests in the central Pacific, but the recordings also contain many natural sounds produced by earthquakes, volcanic activity, and whales. Of particular interest are sounds produced by large baleen whales since these animals spend much of their lives in pelagic environments, making their assessment difficult by traditional means. Fin whales (*B. physalus*) and blue whales (*B. musculus*) produce calls with the lowest-frequency and highest source levels of all cetaceans (Richardson *et al.*, 1995). Estimating absolute abundance directly from acoustic recordings requires understanding the acoustic behavior of the whales to a degree beyond our present state of knowledge. In most cases, the signal level of the marine mammal call is too low and the spacing of the available hydrophones too great to allow direct localization. However, minimum abundance estimates can be derived from an isolated hydrophone if the range for each of the calling whales can be accurately estimated. Absolute abundance estimates may ultimately be achieved by deriving empirical calibrations from acoustic recordings obtained from areas where population density is known from visual census efforts.

In this paper, a method of population assessment based on acoustic techniques is applied to the study of fin whales (*B. physalus*) using a seafloor hydrophone located off the island of Oahu, Hawaii, an area where so few fin whales have been seen that their density has not been previously estimated (Mobley *et al.*, 1996). Based on acoustic data from this one hydrophone, a minimum density estimate of fin whales at this site (0.081 animals/1000 km^2) during peak season is derived. Finally, criteria are proposed by which call abundance at a site can be measured to ultimately provide an empirically calibrated population density estimate.

I. METHODS AND RESULTS

A. Point transect surveys

The point transect population survey method consists of measuring call density at multiple geographic locations to estimate average density for a region. Each call density estimate consists of the number of acoustic detections, with associated ranges, per time period. In contrast to visual fin whale distance sampling data where detection rates decrease with range out to a maximum of about 6 km (Clark and Fristrup, 1997) because it is more difficult to see more distant animals, ocean acoustic data for fin whales from a deep-water hydrophone have a relatively constant detection rate out to about 20 km where variability in ambient noise levels and in call source levels combine to obscure some calls. Given the long-duration continuous observation periods of seafloor recordings, enough detections are recorded, even in a low density area such as our example, to allow data from beyond about 20 km to be truncated such that we assume all calling animals are detected in the reduced survey area. In our data the detection ranges were scored at the closest point of approach, resulting in a bias towards more detections at short range. While this bias might be treated statistically based on speed of travel calculations, the observed increase in detections at short ranges is not so large as to believe the intermediate and long range data has a significant bias.

The two primary questions which this paper addresses are how to define a detection and how to determine the range to each detection. The observer disturbance problem, so common in visual distance sampling surveys, is nonexistent for moored hydrophones, but the problems of clustering, animal movement, and multiple counting of the same animal remain. The most obvious problem with estimating population density using single hydrophone data is that if only one point, the hydrophone location, is sampled, a few resident whales could produce the vast majority of the calls. Multiple hydrophone locations are needed before extrapolating such a population density estimate to a much larger area.

B. Kaneohe hydrophone data

Near-continuous recordings were analyzed from a hydrophone in 800 m of water north of the island of Oahu, Hawaii (Fig. 1) covering the period August 12, 1992 to April 1, 1993 (232 days). These recordings were originally collected for seismic studies and were digitally sampled at 100 Hz having a low-pass filter applied with frequency response rolloff starting near 20 Hz, the frequency response below 20 Hz being such that the ocean ambient noise spectrum appears flat down to about 2 Hz. The longest gap in data recording was about five days and only three breaks lasted more than one day, with overall coverage of 94%. This is one of the same hydrophones used by previous researchers (Northrup *et al.*, 1971; Thompson and Friedl, 1982) to plot the time distribution of whale calls. One difference between this study and previous work is that earlier researchers recorded on analog tape and relied primarily on listening to the sounds played back at higher speeds to identify whale calls, while in this study spectrograms were reviewed visually for all data. Only detections which have a signal-to-noise ratio (SNR) greater than 1.0, over the 2–25 Hz band as measured from a waveform plot, are scored. The details of software and spectrogram parameters used in viewing the data are irrelevant as any reasonable choices can detect signals with a waveform SNR below 1.0. One of the authors (M.A.M.) reviewed and scored all 232 days of data in its entirety, a task which required three week's effort.

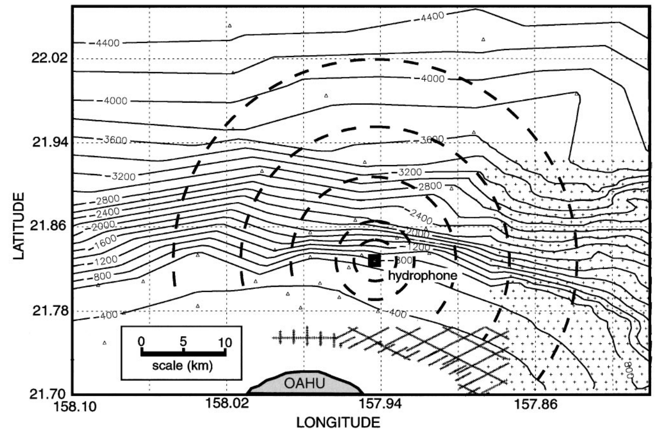

FIG. 1. The location of the Kaneohe hydrophone is shown off the north coast of Oahu, Hawaii. The bathymetry is contoured in meters, the plus symbols indicating digital data points from hydrographic surveys and the triangles indicating data transferred from published nautical charts. The arcs overlain on the map define the zones into which the acoustic survey data was divided.

For comparison purposes, the same percent occurrence scaling used by Thompson and Friedl (1982) is plotted in Fig. 2. This plot scaling, where a day was scored if a call was heard during that day, was more logical for their data, where only about 8 h of data were analyzed per day and there were many gaps in the data. Fin whale calls were observed for 627 h ($\sim$12.5%) of the more than 5000 h of data from the 232 days we analyzed, where breaks in calling of less than 1 h were regarded as continuous fin whale calls. Most of the occurrence data from the Thompson and Friedl (1982) study utilized data from two hydrophones, 11.6 km apart monitored for about 8 h per day, while only one of those two hydrophones was available for this study. Differences in occurrence percentages are likely due to the use of one hydrophone versus two, the increased hours per day of observation and the different methods of detecting whale calls (listening versus spectrogram review). The increased percentage of fin whale calls detected is not useful in relative abundance terms because of these differences, even if we assumed call behavior were the same through the years. Seasonality is similar to that observed by others (Northrup *et al.*, 1971; Thompson and Friedl, 1982), although the increased number of observations provides a more precise measure of occurrence than the previous studies.

C. Call description

The relatively short duration of fin whale calls (about 0.8 s) makes them well suited to range estimation with mul-

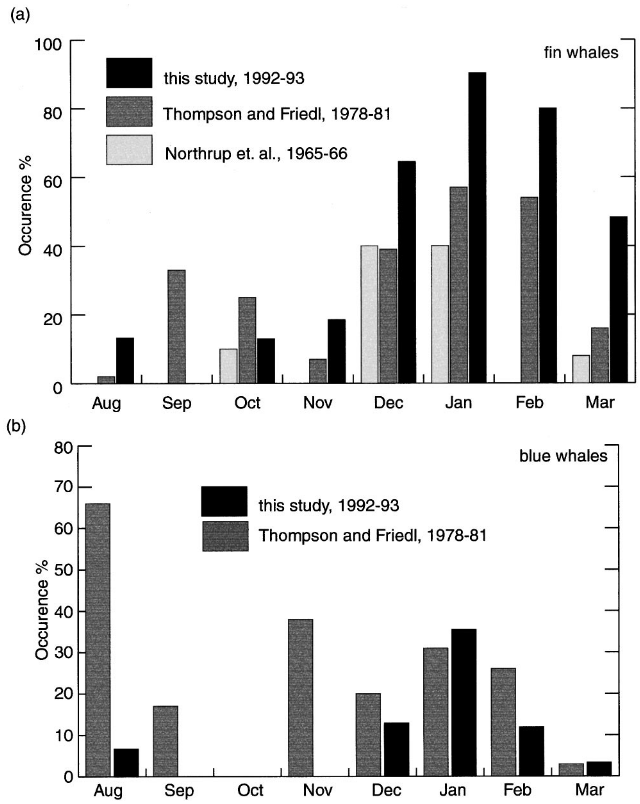

FIG. 2. (a) The occurrence of fin whales from August 1992 to March 1993. Occurrence is expressed as the percentage of each month's total recording days on which fin whale calls were received. The results of studies undertaken from 1965 to 1966 and 1978 to 1981 are plotted for comparison. (b) The occurrence of blue whales plotted as above.

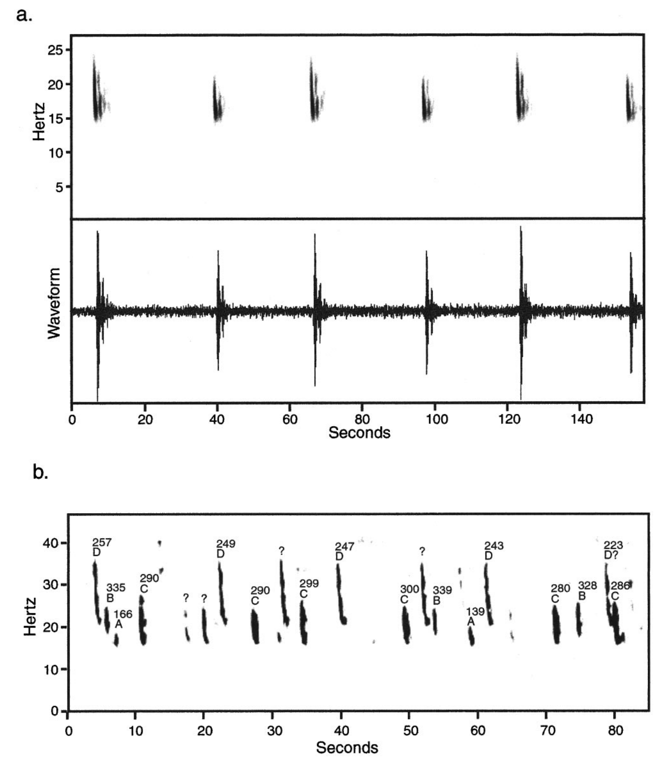

FIG. 3. (a) A typical fin whale call series of the ''20-Hz doublet'' type is shown in spectrogram and waveform. The direct path arrivals are loudest in this example with a SNR of about 12, measured as the ratio of the loudest arrivals to the background noise level on the waveform display. (b) The ''20- to 35-Hz irregular repetition interval'' call type as recorded on a DIFAR sonobuoy October 12, 1997 off Southern California. The compass bearing to the whale is shown above most calls as computed from DIFAR processing. The calls are labeled A through D to suggest that at least four individuals are involved as inferred from call character and bearings. At least three fin whales and one blue whale were visually seen generally to the northwest of the sonobuoy within 1.5 miles.

tipath (echo) techniques. Fin whale calls from the area of this study have been previously categorized into three types, based on the pattern and frequency range of the 0.8-s pulses (Thompson *et al.*, 1992; Thompson and Friedl, 1982). The ''doublet 20-Hz'' calls are well known from both Atlantic and Pacific Oceans and are the dominant call in lower latitudes, making up more than 90% of the calls recorded in this study. An example of typical ''doublet 20-Hz'' calls from this study is shown in Fig. 3(a). Field observations indicate the individuals producing such calls to be smaller (female fin whales are generally larger than males), which together with the seasonality of the calls has led to the suggestion this is a male breeding call (Watkins *et al.*, 1987).

The second call type, sometimes called the ''20- to 35-Hz irregular repetition interval'' type, has been confirmed by analyzing several hours of field data collected with sonobuoy arrays where simultaneous visual observations confirm these calls to be produced by fin whales. Review of hundreds of hours of unpublished fin whale call data recorded on seismology and military systems indicates that at higher North Pacific latitudes in summer more than 90% of fin whale calls are of this higher-frequency countercall type. An example of this second call type is shown in Fig. 3(b), from a recording made with a DIFAR sonobuoy deployed to the southeast of a group of at least three fin whales which were very active though changing swim directions often over an area of about 1.5 miles diameter. Visual position tracks for each whale could not be maintained as it was impossible to keep individual fin whales separated. One blue whale was also present. This recording was made off Southern California (33°31.96′ N 119°44.54′ W) on October 12, 1997. The compass bearings to the whale are shown in the figure for most calls, as computed from post-cruise DIFAR processing (D'Spain, 1994). The call character appears to be a ''signature'' correlated to individuals, as the bearings are nearly the same or smoothly varying for each call character yet different between each call character.

The third call type, ''30- to 90-Hz shorter and more irregular repetition intervals'' call, represents a small fraction of the total in both seasons and all latitudes. Other known fin whale call types include a variety of relatively quiet moans and belches, as well as single 20–35 Hz pulses or series of just a few 20–35 Hz pulses. These less common calls were ignored in this analysis because of the uncertainty whether a fin whale or another species produced the sound. The spectral character of fin whale pulse sounds consistently shows a downward sweep in frequency through the typical 0.8-s duration (Edds, 1988; Thompson *et al.*, 1992; Watkins, 1981).

Essential to our approach to counting fin whale detections is our belief that the loudest calls typical of each sequence of ''20-Hz doublets'' have source levels consistent (within a few dB) from one encounter to the next or have a variability which can be statistically characterized. Knowledge of absolute source levels is not critical to our method. Source levels for fin whale calls of the ''doublet 20-Hz'' type have been reviewed by others (Payne and Webb, 1971; Watkins *et al.*, 1987), reporting wide ranges which have little relevance to our problem as we only score typical, not unusual fin whale calls as detections. A typical detection consists of hundreds of calls in total and dozens of calls which are used to estimate an average for scoring the highest SNR. Of more interest is the median source level which has been reported as 80 dB *re*: dyne/cm^2 at one yard which translates to 179 dB *re*: μPa @ 1 m (Payne and Webb, 1971). In our observations and that of others (Patterson and Hamilton, 1964), source level is consistently louder on the alternately occurring wider bandwidth pulse of the patterned ''doublet 20-Hz'' type calls. We score only the louder of these two types. The initial and final few calls of a series are commonly less loud.

D. Range estimates from call echoes (multipath ranging)

When the typical 0.8-s duration fin whale calls are recorded in water deeper than about 600 m, the received sound consists of three or more distinct multipath arrivals corresponding to the direct path and the echoes which are reflections between the sea surface and seafloor. Localization of sound sources using multipath information from single hydrophone data is a well-established method (Frazier and Pecholcs, 1990; Hassab, 1976; Westwood and Knobles, 1997), although it has generally not been applied to whale calls. Using pre-existing bathymetric knowledge in the vicinity of the deep-sea hydrophones, ray-tracing methods can be used to calculate the time separation between successive multipath arrivals as a function of range and of the bathymetry between the hydrophone and the calling whale. Examples of fin whale calls recorded from different ranges are shown in Fig. 4. A suggestion that fin whale ''doublets'' may be caused by reflections from inside the earth, as deep as the mantle (Premus and Spiesberger, 1997), is not supported by our own transmission loss estimates, the long time intervals (greater than 30 s) common in our data or by the variability in such intervals at a single site. Because of the considerable effort involved in estimating range by this method for each whale call series, this technique may best be applied as a calibration check for the transmission loss method of range estimation.

Recordings from a deep-sea hydrophone on a flat seafloor would be the simplest to analyze in terms of translating echo arrival time differences to ranges. The time differences would be relatively large because of the deep water and independent of azimuth because of the flat seafloor. An example of such multipath time differences is plotted in Fig. 5 for a hypothetical hydrophone on a flat seafloor in 4000 m of water, a typical seafloor depth. A simple ray-tracing algorithm (Coates, 1989) using a constant velocity sound speed profile was used to calculate this example. As arrival time differences can be readily picked to an accuracy of less than 0.1 s, either visually or by cross correlation with a representative call, the range accuracy is on the order of a few tenths

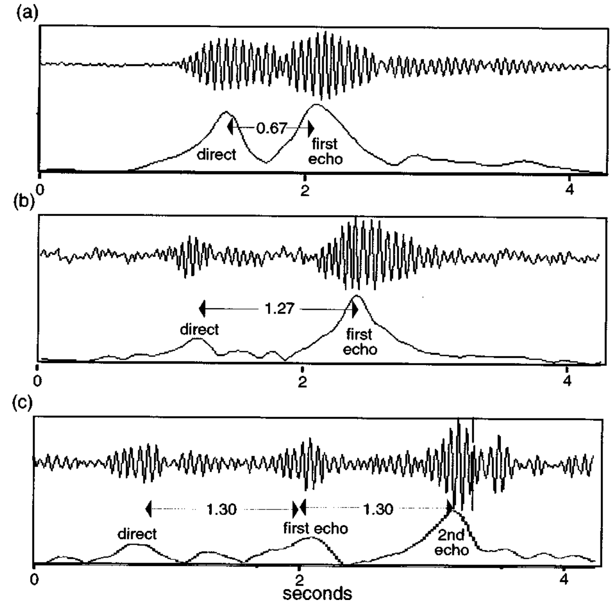

FIG. 4. (a) A time series and a cross correlation of that time series with a representative fin whale pulse are plotted where the fin whale is located upslope of the seafloor hydrophone at about one km horizontal range. The two distinct pulses are the direct arrival and the first seafloor→surface→hydrophone echo path arrival. Other echoes are seen later. (b) The time series and cross correlation is plotted for a whale downslope at about the 4-km range. The first or direct arrival has diminished more than the reflected path because of refraction within the water column. (c) The time series and cross correlation are plotted for a whale downslope at about the 10-km range. The direct arrival is not apparent.

of one kilometer over the first ten kilometers with decreasing accuracy at longer ranges (Fig. 5). In deep water, seafloor recordings typically show a direct arrival and three or more separate bounce path arrivals when ranges are less than 10 km (McDonald *et al.*, 1995). At ranges between 10 and 25 km in lower latitude waters, the direct path arrival is greatly diminished because of refraction within the water column, but the reflected path arrivals remain, thus detectability of the signal changes little. In high-latitude waters, the multipath method is expected to work better than in lower latitudes because shadow zones are less prominent.

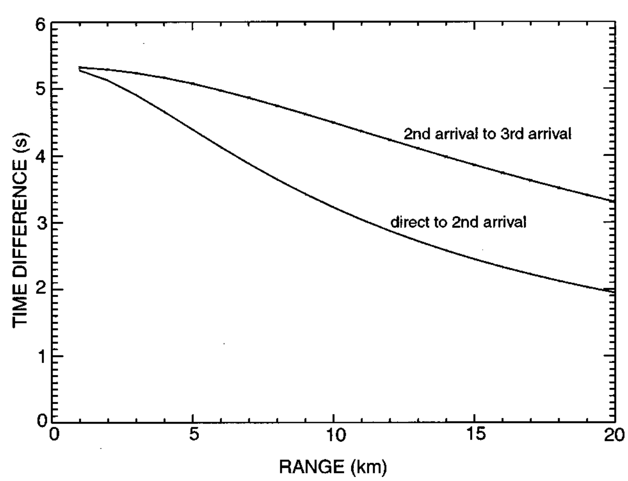

FIG. 5. The differences in arrival times for the direct path and first two bounce paths are plotted for a hypothetical receiver in 4000 m of water with a flat seafloor.

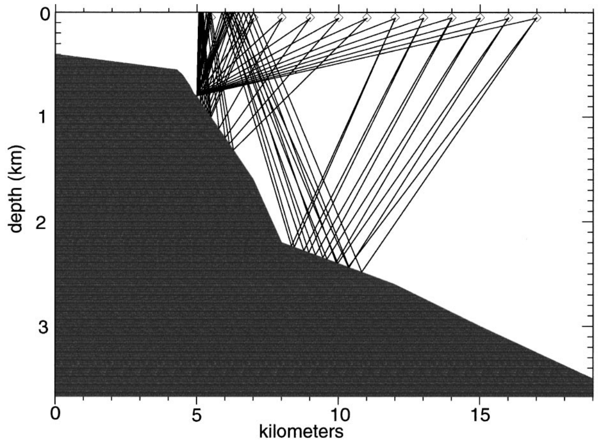

FIG. 6. A bathymetric profile is shown across the Kaneohe hydrophone with the isotropic acoustic travel paths shown for the direct and first two bounce paths shown from evenly spaced source positions.

The rapidly changing bathymetry in the vicinity of the Kaneohe hydrophone makes range determinations using multipath methods much more complicated than would be the case in a flat seafloor environment. Figure 6 graphically shows echo travel paths for a bathymetric profile extending offshore from the Kaneohe hydrophone, an area of steeply sloping bathymetry. Irregular bathymetry opens the possibility of inverting the travel time difference data for a unique position or track for the calling whale, but complicates the estimation of range. Figure 7 shows the two contour maps of time differences for the first three acoustic travel paths. The accuracy of these maps is controlled by our knowledge of the bathymetry, which in this case was largely taken from the nautical charts. Inversion of echo time differences from a single hydrophone for a unique whale position would require better knowledge of bathymetry than provided by the nautical charts for this area. Multipath analysis of some of the nearer whale calls shows that the whales are about as commonly found inshore of the hydrophone as offshore from it. Because of the difficulties presented by the rugged and poorly known bathymetry, we have only used multipath techniques for validation of transmission loss range estimates out to about the 5-km range, a region where spherical spreading losses would be expected in any case. The multipath technique has allowed us to determine that the loudest whales were nearly above the hydrophone (less than several hundred meters horizontal offset), allowing us to transform the transmission loss curve to a range versus SNR plot. In the case of a more ideal hydrophone, the multipath data should be able to verify the spreading loss assumptions out to about 20 km.

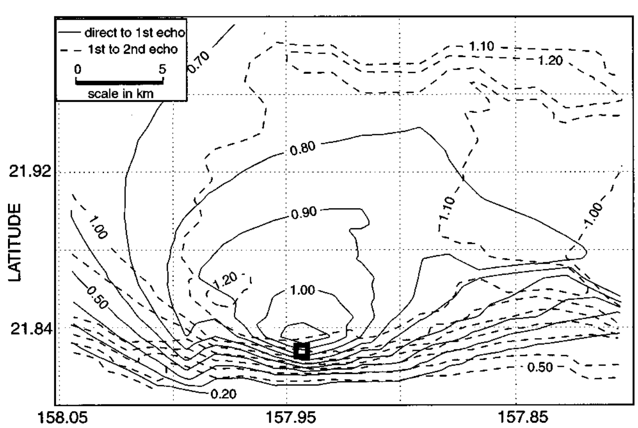

FIG. 7. Two time difference isochron maps are overlain for the area around the Kaneohe hydrophone. Because of the rugged bathymetry the contours are not symmetric as they would be in the case shown in Fig. 5.

E. Range estimates from received sound level (transmission loss ranging)

Estimation of range from received level of whale calls can be accomplished with little effort and independently of multipath methods, although multipath methods can provide a valuable check on the results. Estimation of range to sound sources in the ocean using amplitudes alone requires a reliable sound transmission loss model and the assumption that all the calling whales have about the same maximum source levels during a bout of calling or a statistically characterized variability in source levels. A bout is defined as a series of stereotyped pulses separated by at least 2 h from any other bout (Watkins *et al.*, 1987). Given these assumptions the distribution of the received amplitude data can be used to develop a transform between received level and range. Recording system calibration is not needed nor is any knowledge of the animals' source levels as the relative received levels alone provide sufficient information to fit the data to a transmission loss model, assuming some of the animals pass relatively near the hydrophone. The primary advantage of the relative amplitude and transmission loss approach is that it simplifies the task of evaluating ranges for very large numbers of calls, directly correlating amplitude to range while using the multipath method only to verify the accuracy of the transform.

Theoretical transmission loss calculations such as those performed with parabolic equation methods using the RAM software (Collins, 1993) require knowledge of the sound speed profile within the water column, a bathymetric profile, receiver depth, source depth, and of lesser importance the seafloor characteristics. The source depth, or depth of calling whales, has been reported to be about 50 m for fin whales (Watkins *et al.*, 1987), and analogous blue whale call depths have been precisely measured at depths near 40 m (D'Spain *et al.*, 1995). An earlier report of a single fin whale call at 1200 ft (Patterson and Hamilton, 1964) is believed to be in error because of the difficulty of producing such sounds when the whale's air volume is compressed so small (McDonald *et al.*, 1998). Because the receiving hydrophone is at or below sound channel depths, convergence zone effects are much diminished and water-column sound velocities become less critical to the problem than for a shallow source and receiver. In most cases, transmission loss can be reasonably approximated by simple spherical spreading out to about 15-km range. It may be that a transition from spherical to cylindrical spreading loss occurs beyond 15 km, or it may never occur considering time stretching (Urick, 1983), which is the spreading of the pulse by multipaths as is evident in Fig. 4.

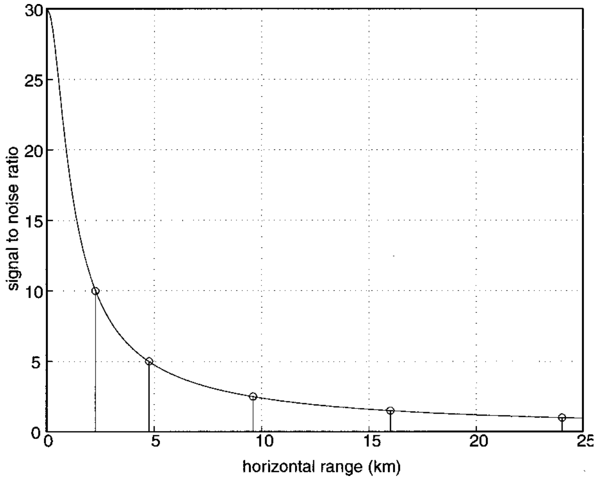

FIG. 8. Spherical-spreading loss ($20 \log R$) is plotted such that the whale calls directly above the hydrophone have the observed SNR of 30. The range of each of the SNR data bins used in the Kaneohe study is shown by vertical lines.

In addition to the assumption of constant or at least predictable source levels there will be a predictable bias associated with changing ambient noise conditions. While ambient noise studies were not conducted for the hydrophone site used in this study, analogous data from near Wake Island (McCreery *et al.*, 1993) suggest ambient noise at 20 Hz increases about 3 dB as wind increases from calm to 13 m/s. At least one other study (Morris, 1978) suggests there is no change in ambient noise levels at 20 Hz in the deep sound channel where the Kaneohe hydrophone is placed. A 3-dB change in ambient noise is equivalent to shifting P–P (peak-to-peak) SNR (signal-to-noise ratio) from 1.4 to 1.0 or from 5.0 to 4.6, thus is significant only for low SNR data. Assuming the transmission loss range data are truncated at an SNR of 1.5, a 3-dB change in ambient equates to SNR variation from 1.7 to 1.3, or a detection range shift from 14 to 18.5 km, assuming spherical spreading loss. This would correspond to a 75% increase in area for our outer survey zone, but this represents the maximum variability rather than the statistical bias. To estimate statistical bias we have assumed a normal distribution for the occurrence of each wind state, with a center at 6.5 m/s based on the number of spectra used for each wind state at Wake (McCreery *et al.*, 1993). The weighted average range for a 1.2 SNR with a nominal 20-km range becomes about 20.5 km corresponding to only about a 5% increase in area. At shorter ranges the effect of ambient noise variability is less, thus we have ignored the bias for all ranges in our analysis.

Transmission losses were calculated for a variety of cases with RAM using typical environmental parameters for this site, an 800-m hydrophone depth, and a source depth of 50 m. A simple spherical spreading loss provides a reasonable estimate of the calculated average results. While transmission loss is usually plotted with log–log scaling using straight lines fitted through the data, it is more useful for our purpose to plot in linear space (Fig. 8). The whales passing nearly overhead the 800-m-deep hydrophone as determined by multipath methods had a SNR of 30, thus defining the range transform for all other calls.

A rough confirmation of the accuracy of our range-amplitude transform is provided by the examination of fin whale acoustic call tracks derived from similar travel time methods and similar arrays of seafloor hydrophones. An array off Bermuda has been able to track fin whales out to 20 km when ship noise is low and the azimuth is favorable (Patterson and Hamilton, 1964); this range corresponds to a SNR of 1.2 by our transform. An array of ocean bottom seismometers in 2400-m water depths found the SNR typically approached unity in the 15–20 km range (McDonald *et al.*, 1995), again similar to our range transform as presented in Fig. 8. Speculations of communication among fin whales over hundreds of miles (Payne, 1995; Payne and Webb, 1971) rely on detection of an omni-directional SNR much less than 1, and thus are not relevant to the methods used here. If a typical whale source level of 176 dB @ 1 m is assumed, the average ambient noise band level at the Kaneohe hydrophone is 88 dB rms *re*: 1 μPa, similar to what is expected from previous studies (Bannister, 1986; Kibblewhite *et al.*, 1976). Hydrophone systems such as used in this study and at Wake Island have electronic noise levels well below ocean ambient levels.

F. Number of calling whales (detection time constant)

For this study, a statistical approach to counting the number of acoustic whale detections using fixed-time duration is proposed. Frequently, multiple whales are calling within the acoustically monitored area, but it is difficult to count each and not double count the passage of a single whale through the area. Using a time constant scoring system, the time periods that include any number of calls are treated as detections over a given time-interval constant. For example, 6 h of continuous calling could be scored as six detections with a 1-h time constant, two detections with a 4-h time constant, or one detection with an 8-h time constant. A typical recording might have 2 h of calling followed by 4 h of silence and 3 h more of calling, a sequence which would score five with a 1-h time constant, two with a 4-h time constant, and two with an 8-h time constant. Based on observations of the duration of call series, a 4- to 8-h time constant appears to represent a good balance between multiply counting a single animal and missing calling animals. In some circumstances it may be possible to separate multiple callers by recognizing multiple ranges, but the inclusion of such information greatly increases the analysis effort required. The detection time constant method provides an easily calculated statistic which can then be calibrated by more rigorous visual or detailed acoustic surveys.

G. Minimum population density estimation

Scoring the number of detections using different time constants provides a range of calling whale density estimates. Call detection numbers and density are shown in Table I for each of the SNR bins. The SNR bins were arbitrarily chosen at levels we judged convenient for separating call series. The areas are computed as the area between range circles except that at ranges beyond 4.75 km, the areas are

TABLE I. Relation of average call density estimate to time constant and range.

SNR	Range (km)	Number of detections $TC=4$ h	Number of detections $TC=8$ h	Call density/1000 km^2 $TC=4$ h	Call density/1000 km^2 $TC=8$ h
1.0–1.5	16.0–24.0	143	85	0.042	0.025
1.5–2.5	9.6–16.0	54	36	0.031	0.020
2.5–5.0	4.75–9.6	15	10	0.016	0.011
5.0–10	2.25–4.75	11	8	0.038	0.027
>10	0–2.25	9	7	0.106	0.083
Average Call Density/1000 km^2 Weighted by number of detections				0.040	0.027

cut off at the 400-m depth to account for the shallow water and onshore zones where whales would not be detected (Fig. 1).

The shortest-range zone will have a higher error due to the relatively small number of detections within that zone and will have a bias toward a higher density because the scoring system assigns the whale to the closest zone it swims through while calling. Using longer time constants increases the bias in detection range estimation toward shorter ranges because the animals have had more time to swim across multiple zones. The longest-range zone may have a larger area surveyed than assumed if the transmission loss does in fact transition from spherical loss to some lesser transmission loss at less than the 24-km range. The intermediate zones between 2.25 and 16 km might be expected to have the most reliable data. The call densities in Table I are averaged throughout the 232 days of the study although the call density varies greatly with season (Fig. 2). The average calling whale density, weighted by number of detections, is 0.027 animals/1000 km^2, for our best estimate 8-h time constant, while the seasonal maximum call density is about three times the average, or 0.081 animals/1000 km^2. The data for a 4-h time constant is shown to provide a sense of the error associated with the choice of time constant. Given that animals producing calls have usually been observed to be part of a group (Watkins, 1981), it may also be appropriate to apply a cluster size to each detection before calibration, further increasing the estimate of acoustic population density.

Limitations of the suggested approach include acoustic saturation, such as has been seen in the California Channel Islands where blue whale calls sometimes continuously overlap each other throughout the day. Our experience with the study site off Oahu and with seafloor recorders off Washington State suggests that the saturation problem is rarely encountered in the deep ocean, the busiest days at the Kaneohe hydrophone having 16 h of calling.

II. DISCUSSION

A. Comparisons with other population density estimates

The best known fin whale population density is that within 100 miles of the coast of California, where extensive visual line transect surveys indicate a population density of 1.1 animals/1000 km^2 (Barlow, 1995; Forney *et al.*, 1995). Several permanent seafloor hydrophones are present off Monterey (Chiu *et al.*, 1997) and off San Nicolas Island (Hildebrand, 1998) which could help to provide calibration for the transform between acoustic call density and absolute population density.

Aerial and ship visual surveys for whales off Hawaii have encountered relatively few fin whales, suggesting fin whale density to be considerably less than that off California (Leatherwood *et al.*, 1988; Miyashita *et al.*, 1995; Mobley *et al.*, 1996; Norris, 1998). As an exercise in estimating the minimum percentage of whales detected acoustically versus actually being present, let us assume the peak density off Oahu equals that off California, although we believe it actually to be much lower. The acoustically detected peak fin whale density off Hawaii (0.081 animals/1000 km^2) then represents greater than 7% of the animals present, a minimum bound. Given that the actual fin whale density off Hawaii is considered to be much lower, we expect we are acoustically counting much more than 7% of the whales present.

B. Detection time constant

A more theoretical approach to estimating the average time constant incorporates swim speed into the calculation. Examination of the multipath information from call series off Oahu reveals the animals to be always or nearly always moving. If the average speeds and monitored area are known, then average transit time can be calculated. Off Bermuda in winter, 117 h of acoustic fin whale tracks were analyzed and yielded speeds of 1.1–4.4 knots (2.0–8.1 km/h) averaged over whole tracks, with the most frequent speeds between 2 and 3 knots (3.7–5.6 km/h) (Patterson and Hamilton, 1964). Calling fin whales in the Northeast Pacific in summer have been seen to travel an average of 8.6 km/h, based on three whales traveling together analyzed over a 1.5-h period (McDonald *et al.*, 1995). There is one report of calling whales in the fall off George's bank which ''move little'' (Watkins *et al.*, 1987).

The Bermuda data are similar to the Kaneohe hydrophone data in call type, season, and setting (near an island), thus tracks from this study are used to estimate average transit time. The average travel speed at Bermuda was 4.65 km/h, but this is reduced to an average straight-line transit speed of 3.25 km/h to account for the zigzag character of the tracks. Assuming a 20-km radius survey zone, the average straight-line transit for whales entering the observation zone is then 9.8 h, but most calling bouts will be of shorter duration resulting in a time constant less than 9.8 h in agreement with our choices of 4 or 8 h as a time constant.

With more data on the call rates of individual fin whales it may be possible to devise a method better than the ''detection time constant,'' but counting the hours during which calling occurs and noting the typical signal-to-noise ratio during those hours have the advantages of simplicity and mimimal analyses time. More sophisticated future approaches might incorporate ''cue counting'' methods (Buckland *et al.*, 1993) which rely on data collected by following individual animals.

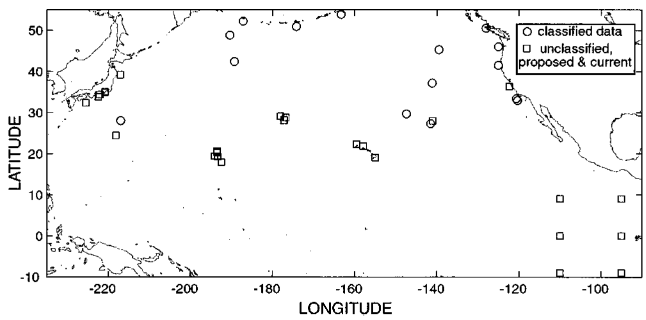

FIG. 9. Permanent and semi-permanent, existing and planned hydrophone locations in the Pacific are shown. Locations of the classified hydrophones are approximate as plotted by Howe and Mercer (1997).

C. The ideal deep sea hydrophone for acoustic whale census

Since the hydrophone sites currently available for marine mammal studies were designed for other tasks, it is worthwhile to consider the ideal configuration for a hydrophone deployed specifically for marine mammal studies. This ideal hydrophone would be below the critical depth (typically about 2000 m for intermediate latitudes) in an area where there is little bathymetric relief within the more or less 20-km range to be surveyed. The reflectivity of the seafloor may also be a factor in the preservation of more or fewer multipath arrivals, a high reflectivity being desirable, although any site will probably work. The location of the H2O seismology station (IRIS, 1998) on a submarine cable between Hawaii and California or the TPC2 hydrophone on a cable between Japan and Guam, in 4000–4200 m of water approaches the ideal. The advantage of being well below the critical depth is noise levels which are 10–20 dB lower (Kibblewhite *et al.*, 1976; Morris, 1978; Shooter *et al.*, 1990), where the distant noise, including distant whale calls, are eliminated and the whale calls within 20 km are more clearly heard. The lack of bathymetric relief allows a simple transform between multipath arrival separations and range (Fig. 5).

III. CONCLUSIONS

Accurate estimation of global whale populations remains a difficult problem that must be addressed using complementary techniques to be successful. This study presents a simple, robust method, although it does include numerous assumptions and caveats, by which acoustic call density can be related to minimum whale population density and later calibrated by proven visual survey techniques. The advantage of acoustic methods is the relatively low cost of placing a self-contained recording instrument at a site where visual observations are often difficult, such as the Antarctic, to obtain a long-term, continuous record of call activity. Recent advancements in the technology of self-contained recording systems make acoustic monitoring an underutilized resource (Fox and Stafford, 1998). Many refinements could be applied to the approach developed here, but calibration of acoustic data with visual survey data is expected to be the most important advance. This approach would work equally well for blue whales except that multipath ranging is complicated by the longer call duration, requiring the application of signal processing techniques (Spiesberger, 1998). The North Pacific alone has over 30 permanent hydrophones either in place or planned (Fig. 9) (Howe and Mercer, 1997; Kinoshita, 1997) and there are many more around the world (Richelson, 1998). If the data from these hydrophones were made readily available, the effort required to establish baseline call densities is relatively small. A crude and simple minimum estimate of fin and blue whale densities around the world's oceans based on acoustic detection could soon become a reality.

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