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Citation: The Journal of the Acoustical Society of America **104**, 3616 (1998);
View online: https://doi.org/10.1121/1.423944
View Table of Contents: http://asa.scitation.org/toc/jas/104/6
Published by the Acoustical Society of America

Long-range acoustic detection and localization of blue whale calls in the northeast Pacific Ocean

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(Received 14 February 1997; accepted for publication 24 August 1998)

Analysis of acoustic signals recorded from the U.S. Navy's SOund SUrveillance System (SOSUS) was used to detect and locate blue whale (*Balaenoptera musculus*) calls offshore in the northeast Pacific. The long, low-frequency components of these calls are characteristic of calls recorded in the presence of blue whales elsewhere in the world. Mean values for frequency and time characteristics from field-recorded blue whale calls were used to develop a simple matched filter for detecting such calls in noisy time series. The matched filter was applied to signals from three different SOSUS arrays off the coast of the Pacific Northwest to detect and associate individual calls from the same animal on the different arrays. A U.S. Navy maritime patrol aircraft was directed to an area where blue whale calls had been detected on SOSUS using these methods, and the presence of a vocalizing blue whale was confirmed at the site with field recordings from sonobuoys.
[S0001-4966(98)01312-5]

PACS numbers: 43.80.Ka, 43.30.Sf, 43.30.Xm [FD]

INTRODUCTION

Blue whales (*Balaenoptera musculus*) have been protected internationally since 1965 (Leatherwood *et al.*, 1983). The numbers of these animals were greatly reduced by whaling and the current global population is not well known. Estimates of the blue whale population in the North Pacific range from about 1400 to 3500 (Mizroch *et al.*, 1984; Yochem and Leatherwood, 1985; Barlow, 1994), and the number of animals found along the coast of central California appears to be increasing (Calambokidis *et al.*, 1990; Barlow, 1994). Little is known about the numbers or distribution of blue whales off the Pacific Northwest. This population was exploited in limited numbers by whalers, particularly in the 1920s and 30s (Pike, 1954; Nishiwaki, 1967; Pike and MacAskie, 1969), but no specific regions of abundance have been described. Most recent work on blue whale distribution and behavior is conducted within accessible, near-shore habitats. In order to study migratory patterns and behavior in the open ocean, a new set of tools is required for long-range detection to allow efficient use of observation platforms and ultimately for indirect study using remote sensing methods.

The U.S. Navy has been recording ''biologicals,'' which includes blue whale calls, on their SOund SUrveillance System (SOSUS) arrays since the system was established in the mid-1950s to track submarines (Nishimura and Conlon, 1994). The SOSUS arrays consist of a series of bottom-mounted hydrophones that relay the received acoustic signals via underwater cables to shore-based facilities for signal processing (Nishimura and Conlon, 1994; Fox *et al.*, 1995). The location of these arrays is currently classified and cannot be discussed here. Despite this restriction, the Navy's hydrophone system is useful for remotely studying whale calls. Because they are bottom mounted, the positions of the multiple hydrophone elements are fixed and the signals can be summed into acoustic beams providing significant signal gain. Given accurate sound-speed profiles, arrival time measurements on only three arrays are necessary for localizing the source of a sound (Watkins and Schevill, 1972). Since 1991 the SOSUS system has been used by the National Oceanic and Atmospheric Administration's Pacific Marine Environmental Laboratory (NOAA/PMEL) in Newport, Oregon, to study underwater earthquakes and volcanoes (Fox *et al.*, 1994). This collected data set, with the corresponding analysis methods developed for seismic studies, can be readily modified to study whale calls.

The approach taken in this study involved several sequential efforts. First, field recordings of calls were made in the presence of blue whales. These recordings were then digitized, analyzed in time-frequency space, and a matched filter kernel was developed to allow detection of the call beneath the ambient noise. The matched filter was then cross correlated with acoustic recordings from SOSUS arrays in the North Pacific to allow the calls to be detected at up to three receiver locations. Epicenter inversion techniques developed for seismic studies were then applied to the arrival times derived from the matched filter output to allow blue whale locations to be calculated at ranges of up to several hundred kilometers. Finally, the methods were applied to real-time recordings from SOSUS to direct a U.S. Navy patrol aircraft to an offshore location where a large whale was

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sighted and blue whale calls were detected with on-site sonobuoys. A match between the calls recorded by the patrol aircraft and SOSUS was confirmed as the same whale by comparison of the acoustic records from these two platforms.

I. BACKGROUND

Although the near-shore distribution of blue whales along California and the Baja peninsula, Mexico is documented (Calambokidis *et al.*, 1990; Barlow, 1994), very little is known about the animals offshore Oregon and Washington. A chart developed from Japanese whaling data shows blue whales distributed over the continental shelf from Baja up to the Gulf of Alaska (Nishiwaki, 1967). Only one blue whale was sighted 80 km west of Cascade Head, Oregon, during surveys from the 100-fa curve to 160-km offshore during winter months from 1959 to 1961 (Fiscus and Niggol, 1965). No blue whales were identified during aerial and shipboard surveys conducted on the outer continental shelf (to 185-km offshore) of Oregon and Washington between April 1989 and September 1990 (Green *et al.*, 1992). Data from Canadian whaling stations indicated that blue whales were found off Vancouver Island, Canada seasonally, with peak abundance (as indicated by catches) in June and September (Rice, 1974). The distribution of these animals has been described as ''well offshore'' (Pike and MacAskie, 1969). While there is some evidence from seismic recordings made at two sites on the Juan de Fuca Ridge (Jacobson *et al.*, 1987; McDonald *et al.*, 1995) that blue whales currently occur in deep water off Oregon, there are no defined regions that can be used as a target for vessels or aircraft interested in finding blue whales for behavioral or population studies.

Low-frequency acoustic signals propagating in deep ocean environments have low attenuation characteristics and thus are detectable over great distances via the deep sound channel (Urick, 1983; Spiesberg and Fristrup, 1990; Spindel and Worcester, 1990). Mysticetes generally produce low-frequency signals that are probably used for communication (Reysenbach de Haan, 1966; Evans, 1967; Winn and Perkins, 1976; Thompson *et al.*, 1979). Calls of baleen whales have been classified into three groups by Clark (1990): (1) simple calls, which are usually low-frequency (<1000 Hz), frequency modulated signals; (2) complex calls which are broadband signals ranging from 500 to 5000 Hz; and (3) clicks, knocks, or grunts usually of short duration and variable frequency. Currently, most of what is known of blue whale calls consists of simple calls with fundamental frequency ranges reported from about 16 to 25 Hz. Such calls may be used for contact among conspecifics due in part to the low attenuation characteristics of subsonic frequencies (Payne and Webb, 1971; Clark, 1990). Blue whale calls have been reported in the literature for animals in the southeast Pacific (off Chile) (Cummings and Thompson, 1971), the northwest Atlantic (Edds, 1982; Mellinger and Clark, 1995), the central Pacific (Thompson and Friedl, 1982) and the northeast Pacific (McDonald *et al.*, 1995; Thompson *et al.*, 1996; Clark and Fristrup, 1997; Rivers, 1997).

The use of acoustic techniques to determine numbers and distributions of calling whales has been particularly successful with migrating bowhead whales. Clark and Ellison (1988, 1989) were able to provide an estimate of the number of calling whales passing a hydrophone array off Pt. Barrow, Alaska during the whales' spring migration. These authors report that a ''sizeable'' proportion of these animals were not in range of visual observation posts and could not, therefore, have been counted in visual censuses. Because not all bowhead whales call while migrating and a variety of factors affect the ability to reliably locate and track whales, visual and acoustic results were combined to provide a more accurate estimate of the population size.

II. FIELD RECORDINGS OF BLUE WHALE CALLS

In August–September, 1993, field recordings were collected in the presence of approximately 14 blue whales between 37–38 °N and 122.4–123.5 °W on five dates: 26 and 28 August and 6, 15, and 29 September, 1993. Recordings were made when blue whales were observed within 1000 m of the Oregon State University 18-m R/V 'Cille. During recording periods, the vessel was stopped and the engines shut down. Recordings were made on both channels of a TEAC Digital Audio Tape (DAT) Recorder; one channel was used to record underwater sounds received through a commercial hydrophone, while the other was used for commentary. The hydrophone had a flat response from 20 Hz to 2 kHz and was rolled off by 3 dB at 12 Hz.

The DAT tapes were redigitized at a sample rate of 256 Hz at NOAA/PMEL in Newport, Oregon using equipment identical to that used to record data from SOSUS hydrophones. This produced a format compatible with the software and hardware used by PMEL for the analysis of SOSUS data. The time series data were processed using a fast Fourier transform (FFT) of 1024 points (25% overlap) to produce spectrograms of the calls. Calls were seen in spectrograms from 10 of the 15 recording sessions (66.6%) or 232 of 322 min (72%). Fundamental frequencies were often difficult to identify from the spectrograms due to interference from local shipping noise, cable strumming, and the roll-off of the hydrophone. Harmonics, however, were clearly visible.

The calls were of two parts. Such multi-part sounds were often described as ''20 c/s long pulses'' and later as parts ''A'' and ''B'' (Thompson *et al.*, 1996). Figure 1 shows one AB call pair recorded off central California in September, 1993. As with the recording of Thompson *et al.* (1996), the field recordings had substantial low-frequency noise that, in all instances, precluded measurement of the lowest A call frequencies. The A calls preceding B calls were detected by their higher-frequency harmonics (Fig. 1). No other whale sounds were identified in these recordings.

In order to better quantify the nature and variability of the calls, time-frequency characteristics of individual calls were digitized from a graphic workstation. The beginning and ending frequencies and duration were measured for each of 303 B calls recorded, including measurements of the fundamental frequency (when visible) and second, third, and fourth harmonics. B calls were characterized by a downsweep of ~1.6 Hz, from 18.9 to 17.3 Hz and lasted 16 s. Table I presents the characteristics of the analyzed blue whale calls, including frequency downsweep and duration for the fundamental frequency and harmonics. Because the

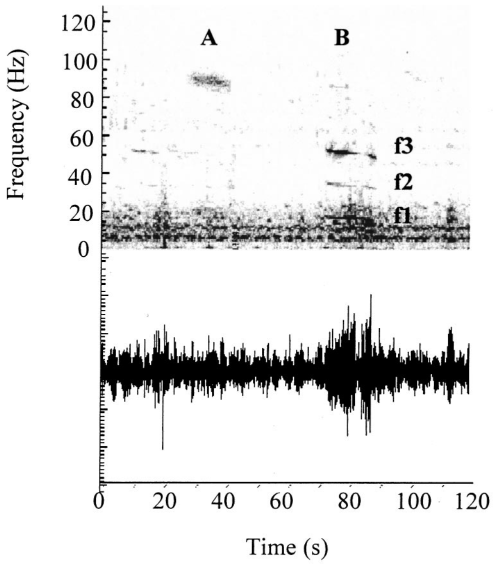

FIG. 1. Blue whale AB call pair from field recordings off California, September 1993. Recordings were collected on a portable hydrophone when blue whales were identified within 1000-m range. Three harmonics of the B call are visible. The A call fundamental is barely visible in the surrounding noise but elements of this call can be seen up to 90 Hz. (FFT size 128 points, 50% overlap.)

fundamentals were more masked by ambient noise, fewer fundamental frequencies were measured than second, third, and fourth harmonics.

III. MATCHED FILTER DEVELOPMENT

A. Background

As noted above, blue whale calls in the northeast Pacific occur near 20 Hz, which is also the range of much shipping noise (Payne and Webb, 1971; Urick, 1983), so the fundamental calls may be obscured by louder ambient noise. A filter that can extract the signal from the surrounding noise is useful for signal detection. Depending on duration and frequency bandwidth, the range at which whale calls can be detected increases by use of cross-correlation techniques (Spiesberger and Fristrup, 1990) such as are used in matched filtering. Matched filters maximize the signal-to-noise ratio of the output by condensing the amplitude of the signal into the output peak (Camp, 1970; Robinson and Treitl, 1980). The gain in signal-to-noise ratio obtained from a matched filter increases with the product of the bandwidth and the duration of a given signal.

TABLE I. Time and frequency characteristics of blue whale B calls used to create kernels for the matched filter. As stated in the text, the fundamental of the A part of the call was obscured by noise.

	B call		
	$f1$	$f2$	$f3$
Duration (s)	16.2±2.7	15.9±2.3	14.9±3.0
Begin frequency (Hz)	18.9±0.4	37.2±0.6	55.7±0.8
End frequency (Hz)	17.3±0.3	34.2±0.7	51.7±1.2
n	16	85	295

A matched filter may be implemented as the correlation of part of a known signal with a noisy time series. For instance, Freitag and Tyack (1993) used 100 μs of a captive dolphin (*Tursiops truncatus*) click recorded on one channel and cross correlated this with input data from other channels to produce peaks in the output which indicated the presence of clicks. They found that this method worked well when the animal was held in a large pen, but when the animal was held in a tank, direct detection without matched filtering of the clicks produced better results. One disadvantage of this approach is that individual variation in calls may produce filters that are overly specific.

For this experiment, only part B of the blue whale call was used. The B call of northeast Pacific blue whales is an excellent signal to model because it is frequency modulated over a long duration. Although there is some variation in individual blue whale calls, all share the downsweep characteristic. A matched filter developed from average values of numerous blue whale calls should be more robust in detecting other calls than a kernel developed from a single call. Because the amplitude of the same call on different SOSUS arrays will differ based on the animal's distance from each array, applying the matched filter developed here will allow for detection of these calls in noisy data. It is then possible to match peaks of the same call on three different SOSUS hydrophone arrays and locate the source of the call. The distributions of calling animals can be extended beyond the range at which calls can be detected by visual examination of the spectrograms alone.

B. Filter design

Mathematical kernels simulating the first, second, and third harmonics were created from mean values of B call characteristics with an inverse Fourier transform. Given the desired sample rate, and estimates of upper and lower frequencies and duration, a complex time series was produced that simulated the Fourier spectrum of a simple linear sweep with these characteristics. The inverse Fourier transform of this model spectrum then produces the time-domain representation of the call.

As an initial test, these matched filters were cross correlated with the data recorded in the field to see if they detected known calls in the data time series. A time series of some of the field data from California that contains two blue whale calls with visible fundamentals and two other calls identified by the presence of harmonics is shown in Fig. 2(a). The results of cross correlating these data with a matched filter developed only from the fundamental ($f1$) is shown in Fig. 2(b). For three of the calls, correlation peaks are produced in the output. When applied to the same data, the matched filter composed of the second harmonic identified the two ''obvious'' calls with correlation peaks that stand further above the noise than Fig. 2(b) [Fig. 2(c)]. The most useful kernel for this data set, however, was that which imitated the third harmonic only. Narrow peaks are produced for four calls and the background noise is reduced [Fig. 2(d)]. This is to be expected; the higher harmonics sweep a larger frequency range, therefore the time-bandwidth product is greater than

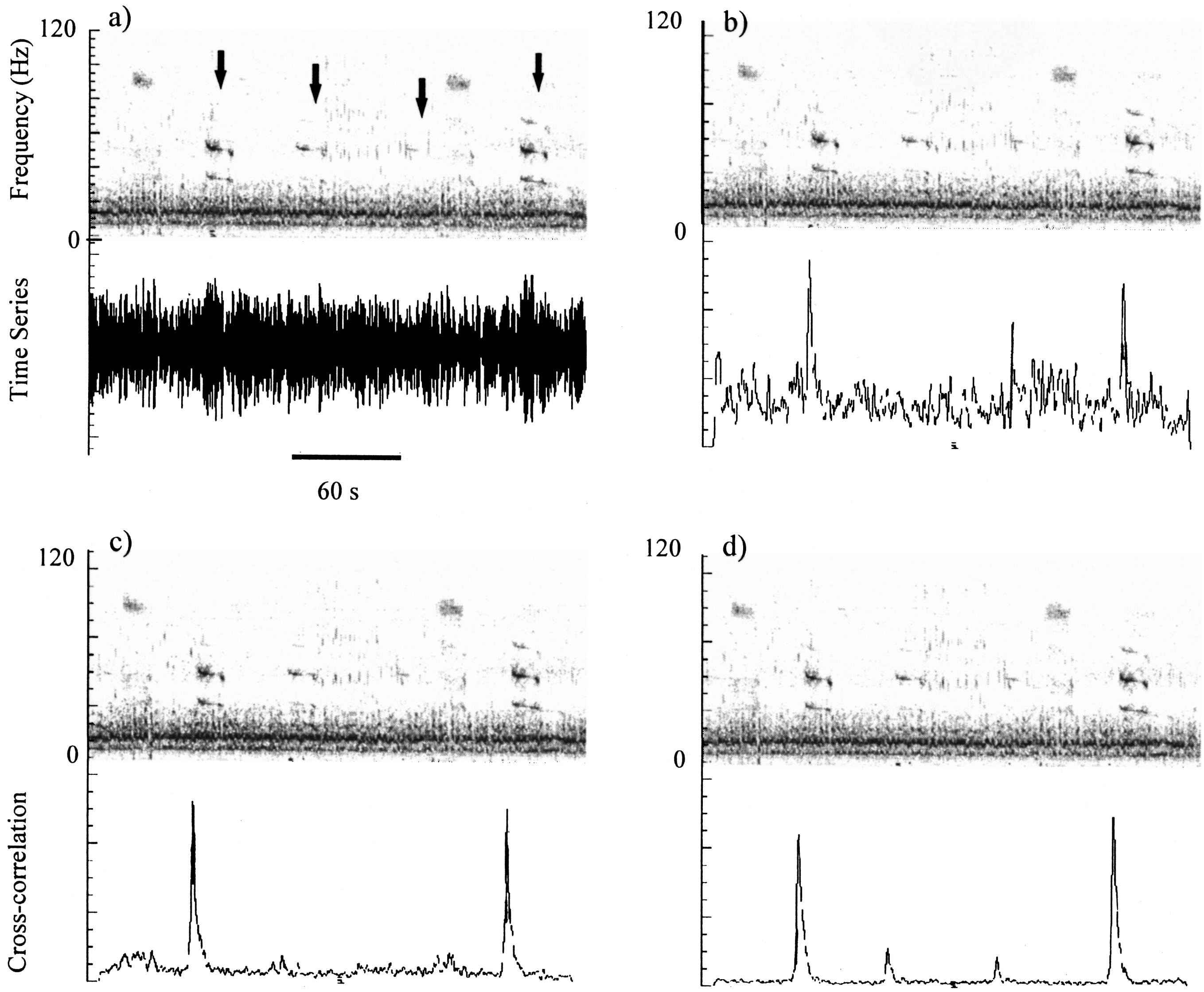

FIG. 2. Average call statistics were used to develop various matched filter kernels to improve signal detection. (a) Time series and spectrogram of four blue whale B calls recorded in the field using a portable hydrophone. Each call is indicated by an arrow; (b) Cross correlation of data from (a) with a matched filter modeled after the fundamental frequency alone; (c) Cross correlation of data from 2(a) with an $f2$ kernel; (d) Same data correlated with a matched filter imitating the third harmonic alone. (FFT size 512 points, 75% overlap.)

for the fundamental. There is also less ambient noise in the 50-Hz range.

C. Application to SOSUS data

When it was determined that the matched filters successfully identified calls in the field data from which they were developed, the kernels were modified to match the 100-Hz sample rate of SOSUS beam-formed data collected at PMEL. These data were originally collected for a geophysical experiment, and were low-pass filtered at 40 Hz; therefore, harmonics above $f2$ were eliminated. Future efforts will sample at 128 Hz and low pass at 60 Hz to avoid eliminating the useful third harmonic. The matched filter kernels were cross correlated with SOSUS data in which there were known blue whale calls, found by visually examining sonograms of archived data files. SOSUS data in which four AB call pairs are clearly visible in the spectrogram, and the results of cross correlation of the $f1$ kernel with these data, are shown in Fig. 3(a). For every B call, a peak is discernible in the output. There are also smaller amplitude peaks where there are A calls. This is probably due to these calls containing a slight downsweep in frequency as well as having a similar duration as the B call. The matched filter was then cross correlated with data from a hydrophone in which there were only faint blue whale calls to determine matched filter performance on low amplitude signals [Fig. 3(b)]. Although the three calls in Fig. 3(b) are not as readily discerned in the spectrogram and not at all in the time series, cross correlation with the $f1$ matched filter produces clear peaks in the signal-to-noise ratio.

While harmonics were regularly seen in the field-recorded data, they were seen less often in the SOSUS data, so a complex kernel was no more successful at detecting whale calls than was the fundamental kernel. The ability of a

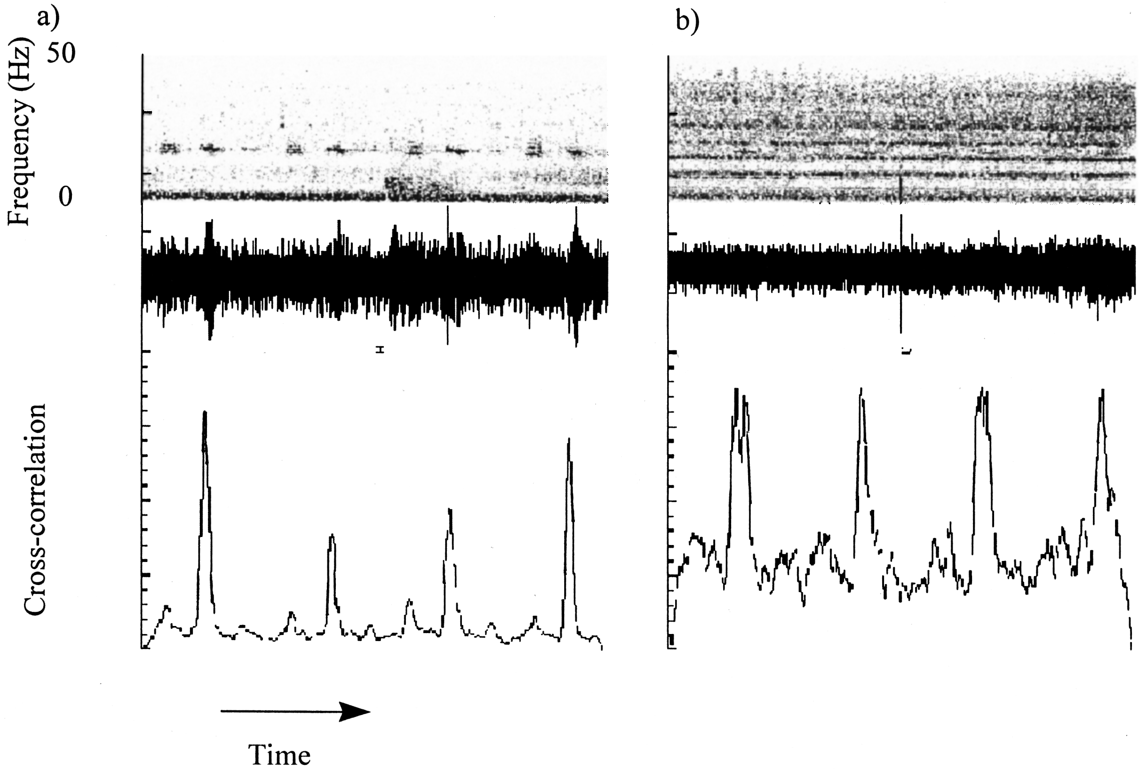

FIG. 3. (a) Spectrogram and time series of four blue whale calls recorded by SOSUS that have been cross correlated with a matched filter developed from portable hydrophone recordings based on the B call fundamental frequency alone; (b) faint blue whale calls from a different SOSUS array and cross correlation of its time series with the matched filter. Although the calls are not visible in either the time series or the spectrogram, the correlation peaks are clear and can be used for timing arrivals.

kernel to detect blue whale calls is determined by how closely the kernel approximates the calls. The matched filter that imitated $f1$ detected calls on both the data from which it was generated and SOSUS data. This result shows that the kernel developed from the field data is general enough to be applied to data not used in the design of the kernel. The relative height and width of the correlation output is related to the amplitude of the call being detected.

It is possible that this kernel may not detect calls of blue whales recorded in different areas, but the procedures used above for northeast Pacific blue whales can be applied to other geographic regions. Cross correlation with artificial kernels such as those developed in this experiment may be better at detecting calls than would use of a single recorded call as a matched filter because the latter would include any ambient noise recorded with that call. Therefore, the output of a correlation with a matched filter would not be as successful if other data had different ambient noise characteristics from the filter.

The success of the matched filter on SOSUS data in which blue whale calls cannot be visually identified by an observer from a spectrogram shows that this method can be used to detect blue whale calls even in a noisy environment or when the calls are of low amplitude. Consequently, the range over which these calls can be detected is increased. It should be possible to create kernels for other low-frequency whale calls, such as finback whale (*Balaenoptera physalus*) calls, and thus increase the utility of matched filters in whale call detection.

Mellinger and Clark (1993, 1997) compared matched filtering with two other methods to determine which was optimal for the automatic detection of whale calls in large data sets. They determined that matched filtering worked less well than either spectrogram correlation or a hidden Markov model at automatically picking calls from data. A matched filter was used for this experiment because detection was only the first step in the two-part process of detecting and then localizing a call. While spectrogram correlation uses the spectrogram itself for detection, the matched filter here was cross correlated with the time series of the data in order that the time of the call could be determined for use in the time delay localization.

IV. LOCALIZATION OF BLUE WHALES

With the successful design of robust matched filters for northeast Pacific blue whale calls, seismic processing software developed by PMEL was modified to allow routine application of the filters to SOSUS data. Up to 15 min of data from three data channels, representing one formed beam from each of the three arrays, were displayed on a computer workstation. Whale calls had to be visible on one or two channels (arrays) for call localization to be attempted. The remaining channel was selected by determining which beam from the third array best intersected the other two beams. The matched filter was applied to all channels, resulting in a composite display of the cross-correlated signal and the spectrogram for each channel (Fig. 4).

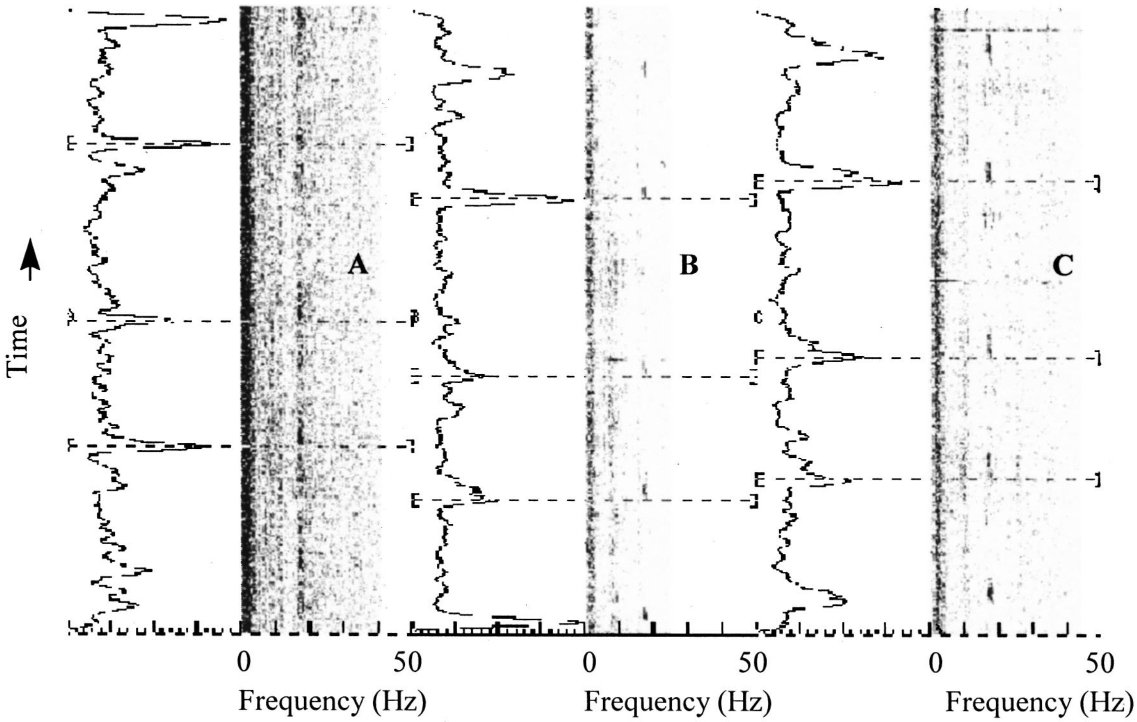

FIG. 4. SOSUS data from three different hydrophone arrays cross correlated with a matched filter based on the fundamental frequency of the B call. The same blue whale calls are visible on arrays A and B but can only be detected on array C when the matched filter is applied. Arrival time picks are labeled 1, 2, and 3. The calls arrive first on array B, then array C, then array A.

The pattern of peaks in the cross-correlated data were compared among channels to determine how the calls were associated. Because a call series often had pauses and variation in repetition rate, identifying the same call on different channels was generally straightforward. When a call was selected, its arrival time at each array was selected. A detailed plot of the matched filter output allows resolution for each pick down to 0.01 s. A display of three picks (1,2,3) is shown in Fig. 4.

The arrival times of the same call at three different array locations are combined with sound-speed models for the northeast Pacific and compared to an initial position of 46 °N/129 °W. A nonlinear least-squares technique is used to estimate source time, latitude, and longitude of the call. It is not possible to determine a quantitative measure of location accuracy with this method as there are no degrees of freedom for calculation of a standard error. However, a measure of the bias in the calculated localization for earthquakes was performed by dropping small explosive shots at known positions. The calculated locations were found to be 1.76 ± 0.76 km south and 0.46 ± 2.04 km west from the known explosive shot points which were deployed at the same range to the SOSUS arrays as the whale calls that were localized (Fox *et al.*, 1995). A Monte Carlo simulation was run using the three available arrays and assuming a rms error of 0.1 s per pick for each hydrophone. This simulation was run with a grid step of 0.75 degrees in latitude and longitude for the region around which whale calls had been localized. Assuming the ability to pick the cross-correlation peak to within 0.1 s, the rms errors for the small region around the blue whale localizations discussed here were $\pm 0.06°$ latitude and $\pm 0.25°$ longitude.

V. GROUND-TRUTH EXPERIMENT

To evaluate the fidelity of locations derived from SOSUS by use of these techniques, an experiment was undertaken to coordinate real-time localization of blue whales from SOSUS data with a Navy P-3C patrol flight operated by patrol squadron VP-46 at the Naval Air Station at Whidbey Island, Washington. Model AN/SSQ-53D sonobuoys were used to relay acoustic signals back to the aircraft via radio links. The P-3C's sonobuoy radio receivers were interfaced to a prototype acoustic tracking system, which provided multiple channels of acoustic data to a processing system. Positions of acoustic sources were determined by arrival time delay analysis. Figure 5 shows an example of the data display received from multiple sonobuoys. Both time-frequency spectrograms and a geographic display are provided to the operator. The locations of sonobuoys are labeled with their radio channels and the resulting source location hyperbolae are also displayed. Three or more buoys are used to form a series of hyperbolae and their intersection depicts the location of the acoustic source.

On 4 August, 1994, a P-3C flight was scheduled. Blue whale calls were seen in spectrograms from SOSUS and locations were determined by the methods described above. A position of 46°36′N by 129°07′W was calculated by NOAA/PMEL personnel in Newport, Oregon and radioed to the P-3C before the 1000 PDT take-off. The P-3C took off from the Naval Air Station at Whidbey Island, Washington at 0955 PDT and began operations at 1129 PDT in this area. Weather conditions were generally favorable with the exception of 25–30 knot surface winds. The aircraft initially dropped a bathy-thermograph buoy in the area of the detec-

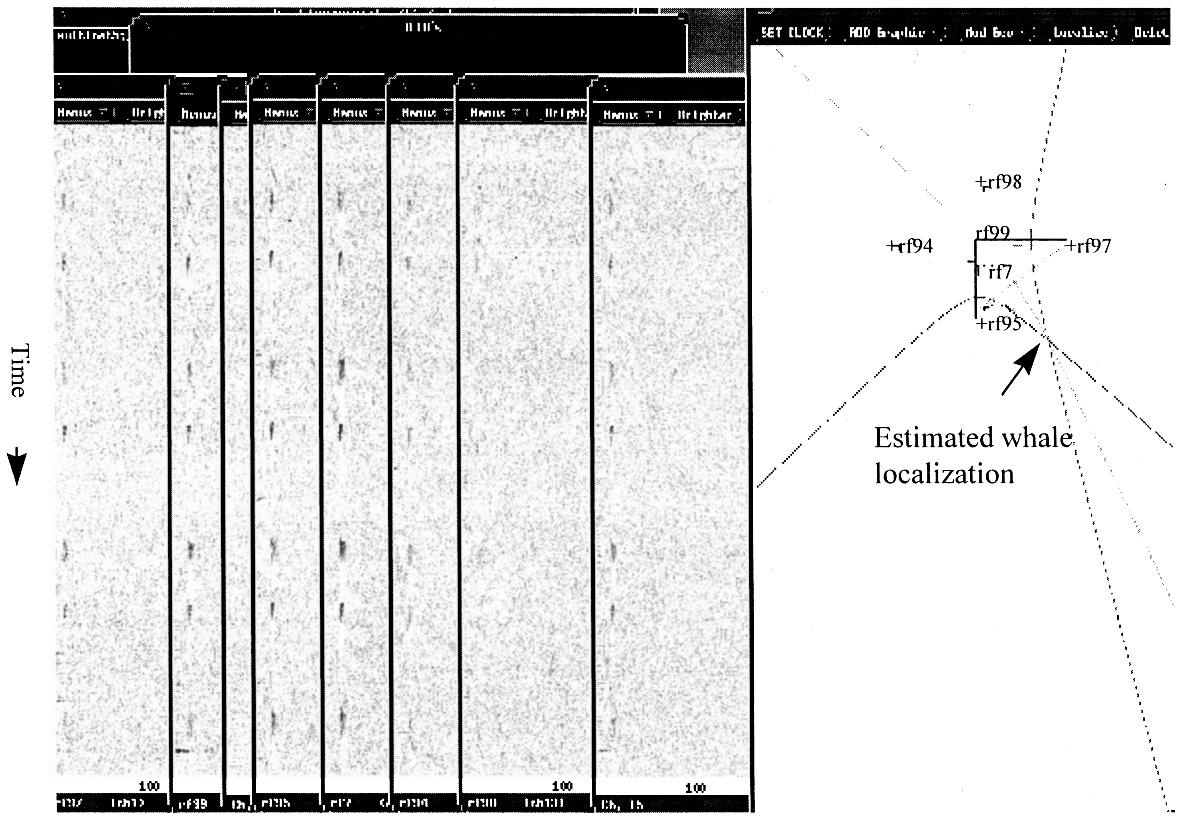

FIG. 5. P-3C sonobuoy display recorded at 1315 PDT. The location of this call series was estimated to be 46°34.0N/128°51.9W. Relative sonobuoy positions and the derived call location are shown on the right side of the figure, while spectrograms of the acoustic signals received from the sonobuoys is shown on the left. Positions of the sonobuoys (in N latitude and W longitude) were as follows: rf7: 46°34′55″/128°59′06″, rf94: 46°35′03″/128°59′06″, rf95: 46°31′15″/128°53′01″, rf97: 46°35′04″/128°47′27″, rf98: 46°39′27″/128°53′03″, rf99: 46°35′02″/128°53′16″.

tion, and the measured sound velocity profile was used to determine the acoustic propagation characteristics of the area. These environmental characteristics were used to establish the appropriate hydrophone depth settings and geographic spacing for the sonobuoys. Sonobuoys were then deployed and signals from the sonobuoys were received aboard the aircraft. Immediately after the sonobuoy deployment was completed (1145 PDT), blue whale calls from a single individual were detected on all buoys and localized. Figure 5 shows an example of such a localization, made at 1315 PDT, in which the source of the calls was estimated to be at 46°34.0′N/128°51.9′W. Since sonobuoys drift away from their original positions on the prevailing currents, the P-3C periodically resurveyed the sonobuoy field, allowing updated buoy positions to be used in the localization calculations.

Following the initial acoustic localization, an attempt was made to confirm the acoustic position by conducting a visual search. This was performed at an altitude of 1100 ft at an air speed of 195 knots. Unfortunately the high surface winds made a visual search for the whale very difficult, despite the known presence of an animal in the area. One of the flight crew briefly saw what he described as a large whale at the surface at 1251 PDT and marked its position as 46°33.7′N/128°51.4′W. Attempts to resight the animal were not successful. The crewman was subsequently able to answer questions indicating that he had seen a large whale, but could not provide enough detail to allow positive species identification. Throughout this phase of the acoustic survey, short-range calls from a single blue whale were detected; no calls from other species were detected.

During post-processing, 21 SOSUS localizations were determined for blue whale calls between 1200 and 1400 PDT. A comparison of the sighting location at 1251 with the

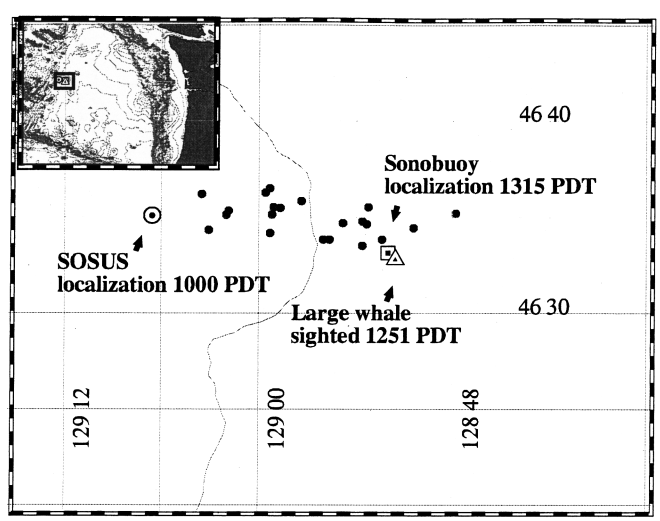

FIG. 6. Map of blue whale call localizations from SOSUS (initial location shown as ⊙, post-processing localizations shown as ●), the Navy sonobuoy localization (□), and the location of the sighting of a large whale (△).

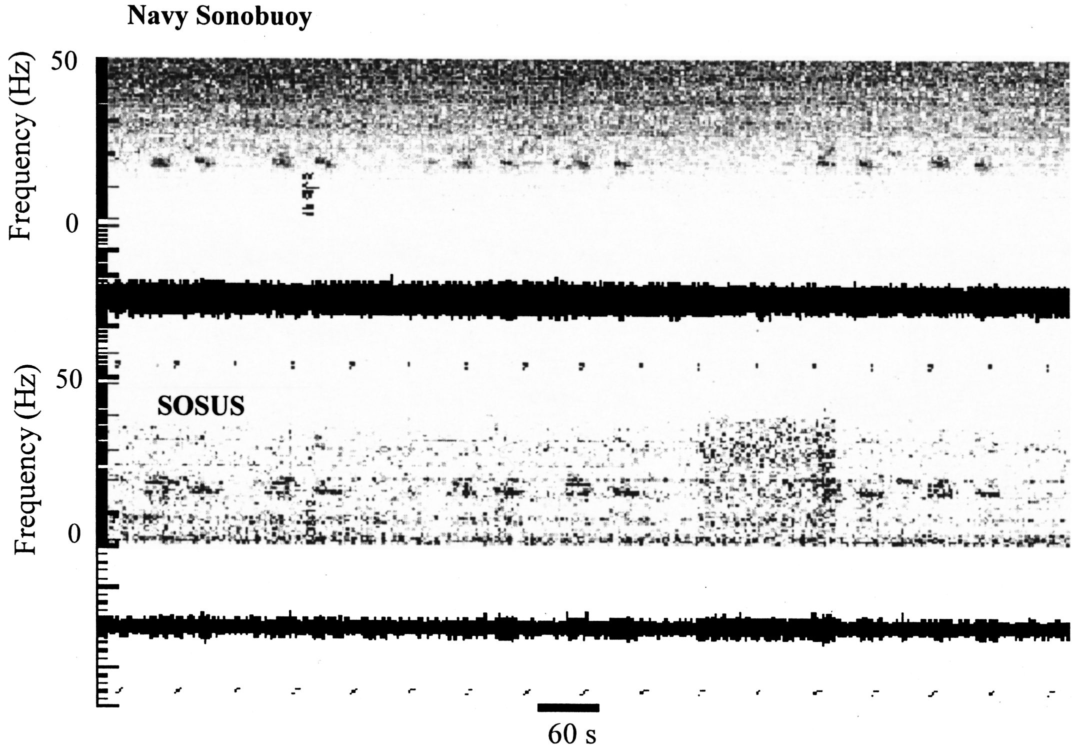

FIG. 7. Side-by-side comparison of six blue whale calls recorded on SOSUS (upper panel) and an air-dropped sonobuoy (lower panel). The spacing and repetition rate of these call series and suggest that they are from the same source, which was later confirmed by their derived locations.

closest time SOSUS localization (1247 PDT) gave a difference of 12.3 km while a comparison of the acoustic localization from the sonobuoys at 1315 with the same call on SOSUS gave a difference of only 2.2 km. A cubic spline was fitted through the 21 locations to generate ''ideal'' straight-line locations of calls. On average, the SOSUS-determined localizations were 2.45 ± 2.25 km from these locations (Fig. 6).

A comparison of the spectrograms from one of the sonobuoys and SOSUS suggests that the animal recorded on these two media was the same. Ninety minutes of available recordings from the sonobuoy with the loudest blue whale calls were compared with SOSUS data from the same time (1300–1430 PDT). Thirty-six AB pairs (72 calls total) were recorded with the sonobuoy array. During this time, 38 AB pairs (96 total calls) were recorded on SOSUS. The two additional calls from SOSUS overlap other calls, indicating that calls from at least two blue whales were detected by SOSUS, but not recorded on the sonobuoys, at this time. The pattern of call pairs from the sonobuoys is exactly matched with SOSUS data. Figure 7 shows six AB pairs from each medium. Range from the receivers varies between 400 and 600 km, suggesting that blue whale calls may be reliably detected at these distances under similar acoustic conditions using the matched filter technique.

VI. CONCLUSIONS

Passive localization of calling animals by use of fixed hydrophone arrays such as SOSUS has many advantages. SOSUS arrays can provide information on the locations of whales over a large area. The animals can be located without being disturbed by nearby ship or aircraft and calls are not masked by noise from these vessels (Watkins and Schevill, 1972). Whale calls can be recorded and localized in poor weather conditions and seasons that are not conducive to visual surveys (Clark and Ellison, 1988, 1989). Additionally, short-term swim tracks generated from SOSUS and the associated gaps in calling may be used as an indication of their behavior and what percent of time animals can be expected to be near the surface and thus observable to visual surveys (Fristrup and Clark, 1997). The coordination of the P-3C flight with shore-based monitoring demonstrates the feasibility of locating an individual calling whale by use of the long-range capability of SOSUS. The direction of a rapid-response, medium-range acoustic search with sonobuoys was used as a proof of concept to validate the acoustic localizations determined by use of SOSUS. Cueing field observations from shore-based monitoring can greatly improve the efficiency of field studies.

Passive acoustic localization alone cannot provide a complete picture due to several shortcomings. First, because they are bottom-mounted in deep water, the SOSUS arrays have very poor coverage of waters over the continental shelf (Fox *et al.*, 1995), which is a primary habitat. Second, there is presently no means of determining other behaviors of the calling animal without visual observations. Third, acoustic data alone provide no information as to the numbers and distributions of noncalling whales. Finally, the individual differences in calls among blue whales have not been sufficiently studied to determine how many individuals are represented in a series of locations. Until some of these shortcomings are addressed, numbers and distributions of calling animals from long-range acoustic monitoring will only provide part of the information necessary to estimate densities. Information resulting from the analyses of multi-mode survey data, such as combining acoustic, visual, and genetics, may be used to overcome some of these problems.

Recently, more effort has been placed on including acoustics in assessing regional concentrations of mysticetes, particularly blue whales, with the aim of better understanding the calling behavior of these animals (Clark and Fristrup, 1997; Teranishi *et al.*, 1997). A number of experiments in the southern California Bight region have combined visual and acoustic ''sightings'' to address some of the difficulties of censusing large whales. Several different combinations of acoustic methods have been coordinated with shipboard visual surveys including the use of towed arrays, local moored arrays, and SOSUS (Clark and Fristrup, 1997), and drifting sonobuoy arrays (Teranishi *et al.*, 1997). Fristrup and Clark (1997) address the advantages of these types of dual-mode surveys and suggest means by which they can best be used to estimate the densities of animals in an area. A combination of passive localization and on-site observations of whales should provide a more complete picture of the animals' behavior while calling as well as the proportion of calling animals in one area. This information is crucial for population estimates based solely on acoustic methods.

Unlike the relatively near-shore efforts in the southern California Bight region, the area monitored by SOSUS in the offshore northeast Pacific is less tractable because the animals occur far offshore. The concentration of blue whales is currently unknown, but may be too sparse to merit the expense of a large-scale visual survey. For the time being, however, localizing blue whale calls offshore of Oregon and Washington will help define regions where the animals do occur. As a database of whale call locations is built up, our understanding of blue whale habitat, relative abundance and seasonality will improve, which may lend itself to a dual-mode survey in the area offshore of Oregon and Washington.

ACKNOWLEDGMENTS

This work was performed as a partial requirement for a M.S. degree in Wildlife Sciences at Oregon State University. Supporting agencies include ONR (Program No. 9310834), the OSU Endowed Marine Mammal Program, and the NOAA VENTS program. Thanks are due to Dr. Bruce Mate for his guidance as K.M.S.' graduate adviser. Additionally, Dr. Christopher Clark of Cornell University loaned the hydrophone and DAT recorder used in the field portion of this experiment. Dr. Mark McDonald provided helpful comments on a previous draft of this manuscript. PMEL contribution #1832.

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