Long-Range Acoustic Detection and Tracking of the Humpback Whale Hawaii-Alaska Migration

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Abstract - **In recent years the Navy has provided the scientific community with increased access to the long-range underwater Sound Surveillance System (SOSUS). One of the first applications of this system was to monitor the migratory behavior of acoustically active pelagic whales (e.g., blue, humpback, finback). In 1995 we compared SOSUS detections of humpback whales with the positions of satellite telemetry-tagged humpbacks. The results suggest that SOSUS can reliably track whale migratory patterns by remote and non-intrusive real-time coverage of large areas of ocean that would be impossible to monitor by any other means. We also discuss the possibility of using SOSUS to estimate whale populations by "turnstile" monitoring of whales passing through a selected portion of the migratory path.**

I INTRODUCTION

The Navy's Sound Surveillance System (SOSUS) is a network of hydrophone arrays dispersed over the ocean basins, including the North Pacific. The hydrophone arrays are connected by cables to on-shore processing facilities. Acoustic data from these hydrophone arrays are processed and monitored continuously. Beamforming of the array data provides high gain directional reception of underwater sounds [1]. The beamformer outputs can be processed into spectrograms that represent the sounds detected by a hydrophone array from a specific direction, and visually examined for interesting signals.

One of the new applications of SOSUS in the post-cold war era is research on acoustically active whales. Blue whales (Balaenoptera musculus), finback whales (B. physalus), minke whales (B. acutorostrata), and humpback whales (Megaptera novaeangliae) are among the louder species that are regularly detected [2] at ranges of about 1000 nm. Several investigations are underway to assess whether SOSUS can reliably track migration patterns and estimate whale populations. Spikes and Clark [3] base their analysis on comparing SOSUS detections with ship or aerial visual sightings. The study reported here is the first attempt to correlate SOSUS detections with the location of satellite telemetry-tagged whales. Our study was coordinated with an experiment by Dr. Bruce Mate of Oregon State University (OSU), who placed ARGOS satellite telemetry tags on six humpback whales to study their spring 1995 migration from calving grounds near the Hawaiian Islands to their summer feeding grounds off Alaska [4].

The position data from the two tagged whales (designated as #10822 and #23038) with the most ARGOS position fixes were provided to us in near real time so we could record and analyze the appropriate SOSUS data. Fig. 1 shows the approximate area we monitored with the three SOSUS arrays (subsequently referred to as S1, S2, and S3), which provided best coverage of the migratory path indicated by Mate's tagged whales.

II THE SIGNATURE OF HUMPBACKS

Humpback whales produce a variety of sounds, but the sounds most frequently recorded by SOSUS are the well-known "songs" consisting of long (7 to 30 minute) structured sequences of sounds [5]. The song components are varied in structure, but most of the energy in the song is contained in the frequency range of 100 to 4000 Hz and typical amplitudes of song elements are 175 to 185 dB re 1uPa at 1 meter [6]. Absorption of sound in water limits the range of undersea propagation at the higher frequencies; at the distances of interest here (> 1000 nm), we are limited to frequencies <300 Hz [1].

The humpback signature is very distinctive from other natural and man-made underwater sounds. Fig. 2 shows a portion of a typical SOSUS spectrogram of humpback whale song. The intermittent horizontal streaks in the upper region of the spectrum are the unique acoustic signatures of humpbacks.

During the three-week period when one or both radio tags were functioning we identified over 30 probable detections of humpbacks.

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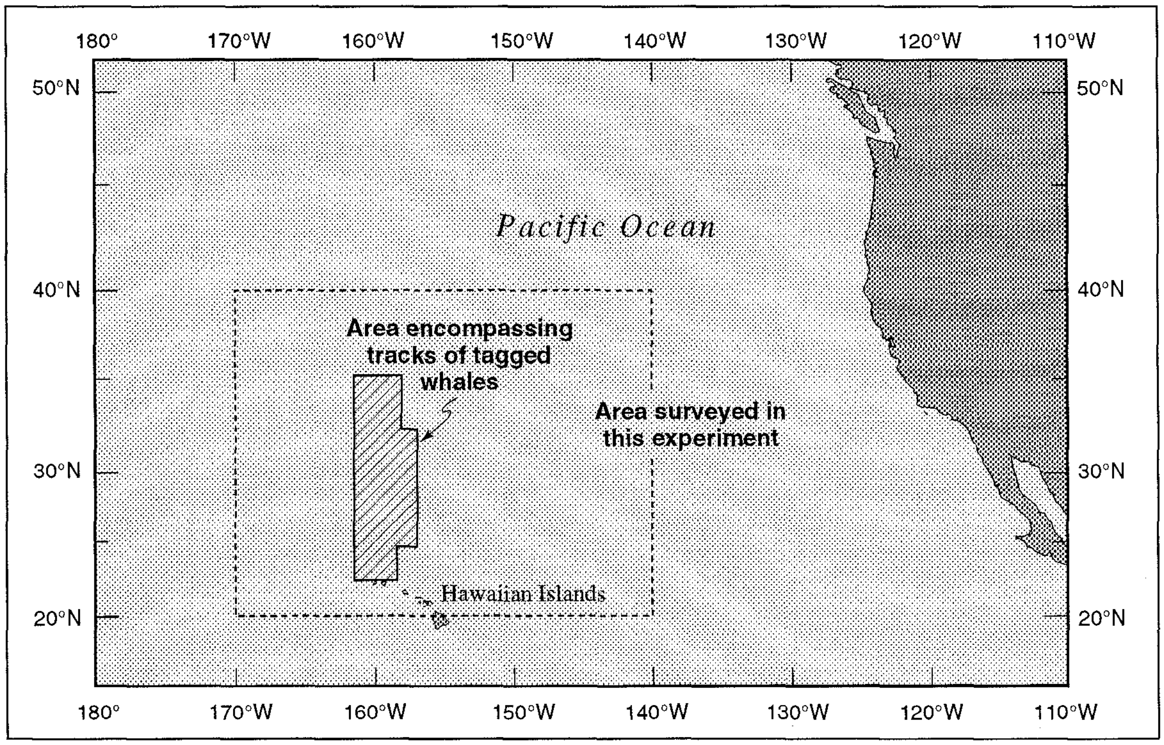

Fig. 1. The geographical areas of the tagged whales and the SOSUS coverage in this experiment.

III COMPARING SINGLE BEAM DETECTIONS WITH TAGS

In Fig. 3 we plotted the bearings of SOSUS detections from array S1 along with the positions of the telemetry-tagged whales translated into array bearings. (Bearing angles are plotted in relative units; actual bearings are classified.) Similar results, but with fewer detections, were obtained on S2.

It is not possible to determine if the acoustically active whales detected by SOSUS were the tagged whales tracked through the same area at the same time, since songs were not recorded from either tagged whale prior to tagging, nor do we know of any documentation of signature features in humpback whale songs. We were able, however, to detect several humpback whale songs at the approximate times and locations corresponding to the tracks of the two tagged whales. These data support the hypothesis that the SOSUS spectrograms of the type shown in Fig. 2 are indeed humpback whales and that the route indicated by both SOSUS and the ARGOS telemetry tags is indeed the migratory path, and not the result of aberrant data from a few wandering individuals.

A general observation on Fig. 3 is that the evolution of SOSUS bearings over time is consistent with the behavior of humpback #10822, both in the period when the tag was functioning, and by extrapolation of the probable evolution after. It is impossible to say, on the basis

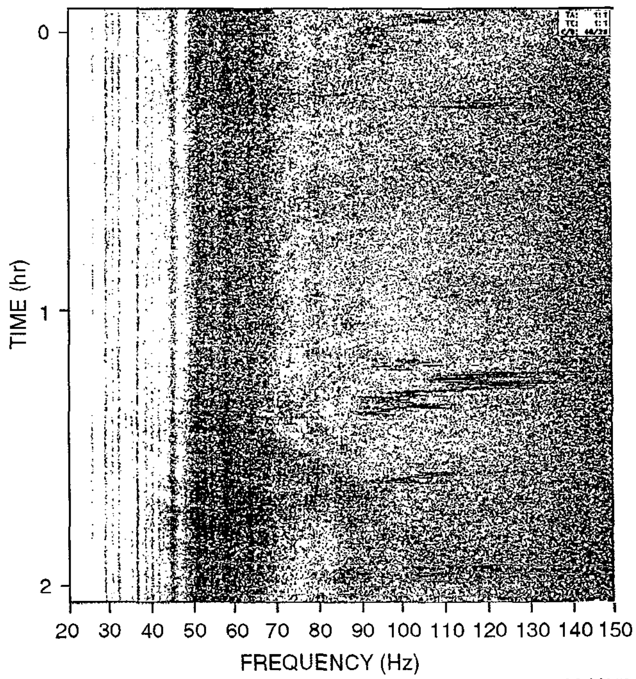

Fig. 2. Typical SOSUS lofargram with humpback vocalizations.

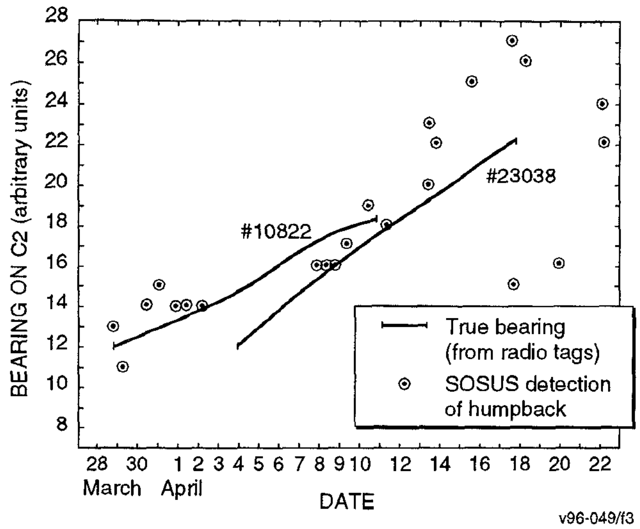

Fig. 3. Comparison of SOSUS detection with radio tag positions.

of this simple analysis, that we detected vocalizations from the #10822 whale. The detections could be vocalizations from other whales migrating in the same general area. The variance in the bearings is too great to assign detections to a particular animal. In fact, over the period April 8 to 12 there are six detections that are equally likely to be #10822, #23038, or another member of the species.

IV Cross-Beam Fixes

We continued to survey SOSUS data for three weeks after the second tag became inoperative, for a total of six weeks of observations, during which many more humpback vocalizations were observed, bringing the total number to about 100. From this set we identified four instances where exactly the same vocalization patterns were detected simultaneously on two arrays. The two bearings provide a cross-fix location (the cross-fixing process is schematically illustrated in Fig. 6). The four resulting localizations, which are shown in Fig. 4, loosely define a "migration corridor" bounded by longitudes 155W and 160W. The four events are not an exhaustive list of two-beam fixes. In fact, with additional signal processing it is likely that all of the roughly 100 detections could be paired up with signals on a second array.

A brief analysis of SOSUS humpback detection from May 19 and May 20, 1996, yielded two more examples of simultaneous multi-array detection. These two cross-beam fixes are separated by approximately 390 nm, and the first occurred roughly 24 hours before the second, indicating that these vocalizations are from different animals. These two fixes, which are included in Fig. 4, fall well within the track of the Spring 1995 humpback migration determined by the 1995 tags and SOSUS data. However, additional 1996 data, still under analysis, suggest that the migration corridor may have shifted slightly east of the 1995 corridor [7].

V Diel Variation in Detections

We grouped the vocalizations into two-hour intervals, making the sample more likely to be statistically independent. A histogram of the 56 grouped events versus local time suggests that the frequency of vocalizations is twice as great in the evening as at other times of the day (Fig. 5). This observation is statistically significant, but further investigation is needed to attribute this result to whale activity, variation in the sound channel, or variations in background noise.

VI Summary and Discussion

Humpback whales were detected on their 1995 northerly migration from Hawaii to Alaska with SOSUS hydrophone arrays. Simultaneously, the progress of two humpbacks was tracked with ARGOS satellite telemetry tags [4]. SOSUS detected many humpback vocalizations on the azimuth directions appropriate to the tagged animals. One of our conclusions from the existing SOSUS data is that we need a more precise localization of the sound source to pin a SOSUS detection on a particular animal.

We cannot be certain that SOSUS detected the same animals, but we can conclude that SOSUS and telemetry tags provide us similar information about the geographical area of the migration, and define a migration longitude corridor between 155W and 160W during that portion of the migration between 30N and 40N. A brief examination of 1996 data yielded two more detections within the same corridor, providing direct acoustic evidence that the humpback migration may follow the same track each year during the northern migration.

One of our future goals is to develop a reliable population estimate from detections made with SOSUS. Fig. 6 depicts a notional concept of "turnstile" counting in which we count the number of detections from a narrow range of bearing angles (the hatched area). The inset in Fig. 6 is an actual count of detections in a 22-day period of the humpback migration. We would use cross-beam fixes to adjust counts for range-dependent probability of detection along the beam axis for single beam detections. Additional adjustment factors would be required for such unknowns as the source level distribution and the fraction of time individual animals vocalize.

Calibration of the probability of detection of whales on SOSUS could also be achieved by simultaneous SOSUS data collection and population surveys by traditional means. We are looking to future NOAA ship-based population surveys as opportunities to make such calibrations.

Still another way to calibrate SOSUS survey data involves making further use of telemetry-tagged whales. We are also looking into using delays in the time of sig-

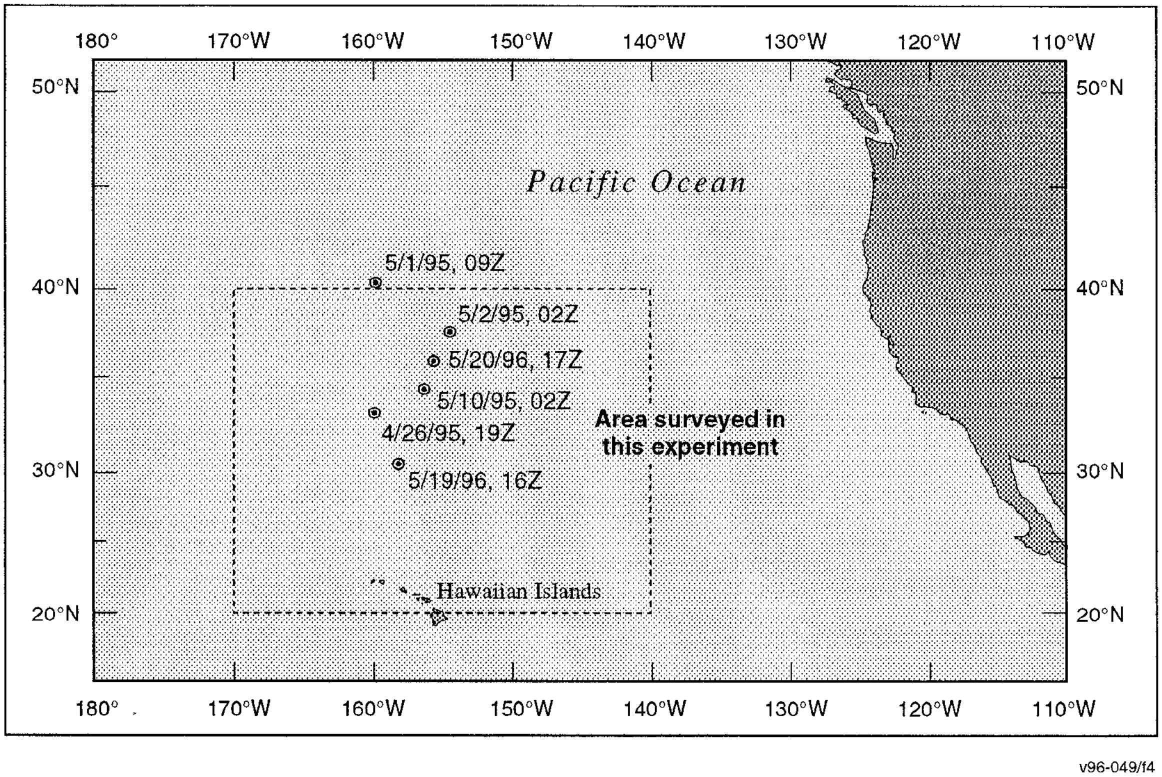

Fig. 4. Locations of humpback vocalizations based on cross-beam fixes.

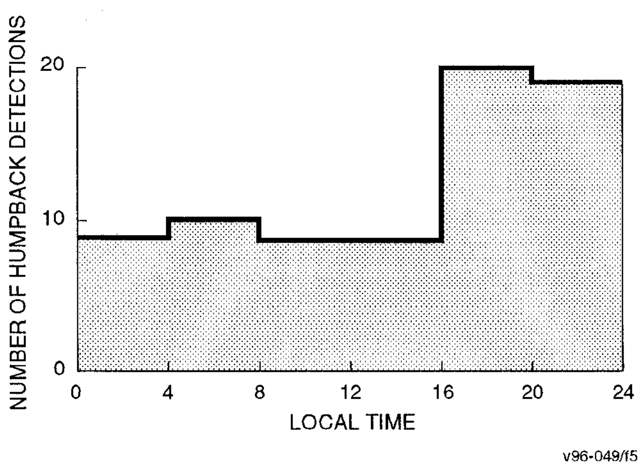

Fig. 5. Diel variability in detections.

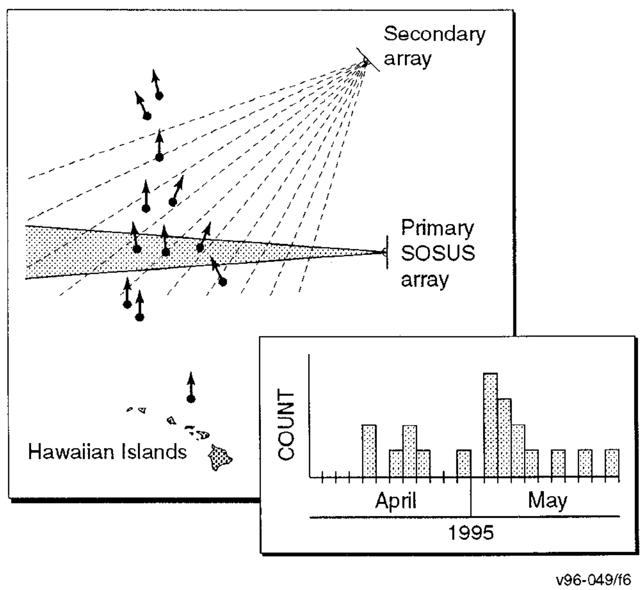

Fig. 6. Notional counter.

nal arrival at two or more arrays to more precisely localize the source of the SOSUS detections. These locations can then be matched with the location of the tagged whales, and subsequently used to track individual whales and use the data from tracked individuals to calibrate the frequency and strength distribution of vocalizations needed to prepare population estimates from SOSUS "turnstile" surveys.

These are the steps needed to realize the full potential of SOSUS as a marine mammal research and conservation tool. This study has shown the considerable potential available from SOSUS right now, using relatively simple and readily accessible signal processing. With SOSUS it is possible to obtain full day, long term, ocean basin scale detection and localization of whales without disturbance. Such data are impossible to obtain by any other means, and a comparable data set obtained by traditional ship or aircraft-based visual observation would be logistically impossible.

VII Acknowledgments

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