An inexpensive passive acoustic system for recording and localizing wild animal sounds

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An inexpensive animal recording and tracking system was designed, which uses sound-recording buoys deployed at several locations simultaneously in a passive hydrophone array. Each buoy contains a global positioning system (GPS) Location logger, a stereo digital audio tape (DAT) recorder with a hydrophone connected to one channel, and a VHF radio signal for time synchronization connected to the second channel. In a calibration test, three buoys were deployed in triangle formation at 1.8-km spacing. Light bulb implosions were localized to an accuracy of 60 m at the array center. These buoys are far less expensive than most marine acoustic tracking systems. The instrument package can be used for drift, moored, or terrestrial applications. © *2000 Acoustical Society of America.* [S0001-4966(00)02906-4]

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INTRODUCTION

Investigators of the acoustic behavior and movements of vocalizing wild animals are challenged by economic, logistical, and technical barriers. These barriers can be especially high in the open-ocean environment, where animals that spend the majority of their time underwater are often far from shore, fast-moving, highly dispersed, and interacting over distances greatly exceeding visual range (Costa, 1993). Addressing questions about social systems, foraging behavior, population densities, and management can be quite difficult.

A common need is to localize and track animals that are underwater, hidden beneath ice, in forests, or otherwise difficult to track visually. The marine environment is a poor conductor of light but an efficient propagation medium for sound. Many marine species, especially cetaceans, have evolved sophisticated sound production and reception mechanisms to aid in meeting their requirements for foraging and reproduction. These species' natural history can be studied through the acoustic signals produced during their activities. Such animals may be tracked acoustically by collecting sound from several locations simultaneously and using time-of-arrival differences to estimate locations (Spiesberger and Fristrup, 1990). Typical tools for acoustic research in the pelagic environment include towed hydrophone arrays, bottom-deployed arrays such as SOSUS arrays, large ships, multichannel signal conditioning/recording systems, and sonobuoy/receiver systems (Nishimura and Conlon, 1994). The price, signal processing skills, and military relationships associated with these systems make them inaccessible to many marine biologists.

To reduce the cost and improve the accessibility of acoustic tracking methods, an acoustic localization system was built consisting of commercial off-the-shelf components commonly available from hardware, marine supply, and audio electronics stores. It consists of several independently drifting, time-synchronized recording systems, similar to sonobuoys in concept except that these are recoverable buoys that record sound data instead of transmitting it by radio. In operation, these buoys record sound signals, time-synchronization signals, and GPS locations. Laboratory analysis of the recordings allows vocalizing animals to be located and tracked.

METHODS

Buoy design

Each buoy contains a stereo digital audio tape (DAT) recorder (Sony TCD-8; frequency response flat ±1 dB from 9 Hz to 22 kHz) with one input channel connected to a hydrophone (Hi-Tech HTI-SSQ-41B; frequency response flat ±1 dB from 10 Hz to 30 kHz) for collecting acoustic data. The second input channel of the DAT recorder receives the audio output of a marine VHF radio receiver; this signal is used during analysis to time-align the sounds recorded on the separate buoys. A nondifferential global positioning system (GPS) data logger (Garmin 45) documents the buoy's position as it drifts during recording sessions (Fig. 1).

Instruments and ballast are encased in waterproof spar-buoy PVC housings for deployment at sea (Fig. 1). The housing design utilizes a spar shape for the buoy. This shape has a small water-plane area, damping the impact of wave

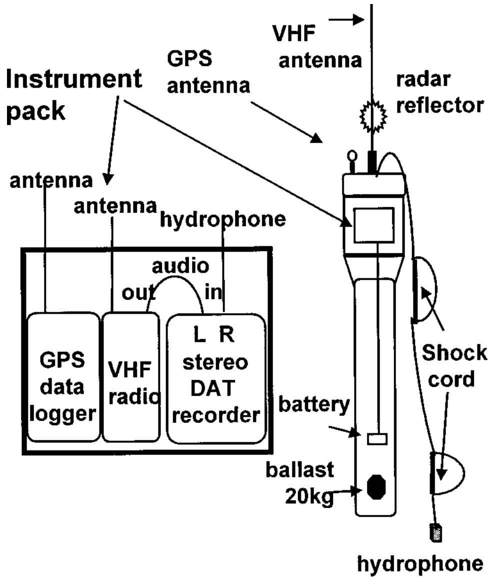

FIG. 1. Spar buoy instrument pack and housing. Each buoy contains an instrument pack with a stereo DAT recorder, a marine VHF radio receiver, and a GPS receiver/logger. The DAT has one input channel connected to an external hydrophone for collecting acoustic data, with the other channel connected to the VHF radio's audio output for time alignment. A 2.2-m waterproof spar-shaped PVC housing encases instruments for deployment at sea.

action on vertical buoy motion and reducing flow noise over the hydrophone. A 1–2-m length of shock cord is attached to the hydrophone cable near the buoy to further damp the effect of wave action and cable strum. Depending on the application and available resources, very high frequency (VHF) radio tags, strobes, and/or radar reflectors can be attached to the buoy to aid in tracking and recovery. Package price is approximately $1900 per buoy.

Deployment

These buoys are deployed in a drifting ring around target animals. Vocalizations are localized using time delays between buoys as explained below. Three or more buoys are needed for a localization system. Deployment time of the buoys in a 1-km triangle grid is approximately 1 h. Time is dependent on the spacing between buoys, sea state conditions, and speed of the deployment vessel. Maximum recording time, about 6 h, is achieved with a 90-m tape and the DAT recorder set to ''long-play'' mode (32-kHz sampling rate). A single recording session can therefore provide 5 h of time-synchronized data.

The hydrophone and cable trail upwind behind the buoy as it drifts. During recovery, it is best to approach drifting buoys from downwind to reduce the chance of propeller entanglement and a lost hydrophone. Moored buoys should be approached from upwind/upcurrent for similar reasons.

Analysis

Localization analysis consists of three steps: time-alignment of the three (or more) hydrophone recordings, determination of differences in times that animal vocalizations occurred in the three recordings, and estimation of the animal's location.

Time-alignment

Each stereo tape recorded in a buoy contains one channel with the hydrophone sound signal and the other channel with audio from the VHF radio receiver. This tape recording is transferred to a computer as a two-channel sound file. Time-alignment of the hydrophone recordings is accomplished using the VHF audio signal. The VHF receivers in all buoys are tuned to the same frequency, so that all the radio receivers relay the same audio signal synchronously. Hydrophone signals from all buoys are synchronized by time-aligning the corresponding VHF radio signals.

Alignment is performed by choosing one buoy as the reference. For the other two ''aligning buoys,'' the stored VHF audio signals are cross correlated with the reference VHF audio signal. The time offset of the cross-correlation function's peak is the amount by which the two signals are offset in time (van Trees, 1968). Each aligning buoy's hydrophone signal is time-shifted to bring it into alignment with the reference buoy's hydrophone signal. After all signals have been shifted and brought into time-alignment, the VHF signals are discarded, and the hydrophone signals are stored as a single sound file containing three time-synchronized channels.

Time-delay estimation

To estimate the differences in arrival times of the animal vocalization at each buoy's hydrophone, either the waveform is measured directly or a cross correlation is calculated. In the direct measurement method, useful for loud, abrupt sounds, the waveform of each signal is examined. The onset time—the instant at which the sound first appears in the waveform—is measured. Time-of-arrival differences between hydrophone signals are calculated by subtraction of arrival times.

In the cross-correlation method, time differences are determined for each possible pair of hydrophones. The portion of two hydrophones' sound signals containing a vocalization are cross correlated. The time-offset peak in the cross-correlation function specifies the time difference between the arrivals of the vocalization at the hydrophones. Cross correlation can be limited to the frequency band of the vocalization, thus removing some noise (Clark *et al.*, 1996).

Location estimation

Conceptually, a time-of-arrival difference between a pair of hydrophones determines a hyperbola on which the vocalizing animal must lie. In an ideal medium, the intersection of all the hyperbolas would be the animal's location. Since there is noise in each of the signals, the hyperbolas do not intersect at exactly the same point. A least-squared-error fit is used to determine the best location.

Calibration

Two calibration sessions were conducted to determine the accuracy of this drifting buoy array over the submarine canyon in Monterey Bay, California, at 36° 47′ N 122° 00′ W, in water approximately 900-m deep. Three buoys were deployed in a rough equilateral triangle

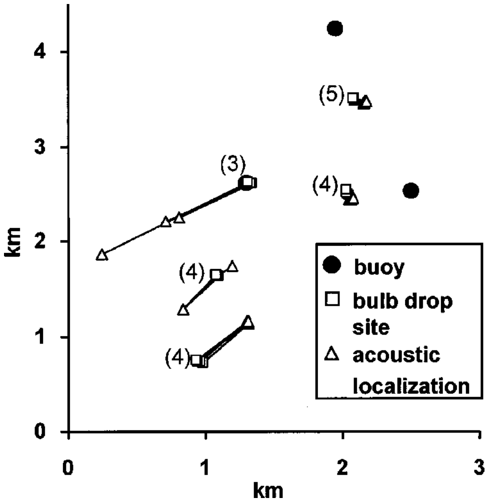

FIG. 2. Calibrating localizations with the spar buoy array. During the second of the two calibration sessions, 20 light bulbs were sunk and imploded around the array. One of the ensuing localizations was rejected (see text), resulting in the 19 localizations shown here. For bulbs dropped within the array, the mean distance between the recorded GPS position of the drop site and the acoustically determined position of each bulb was 73±17 m ($n=9$). For bulbs dropped outside the array, the mean distance was 586 ±299 m ($n=10$). The mean distance for all 19 points was 306±344 m ($n=19$).

approximately 1.8 km per side, with hydrophones at approximately 25 m depth. A total of 30 lead-weighted incandescent light bulbs were dropped and imploded at several positions in and around the array (Heard *et al.*, 1997). Implosions were recorded and localized by the waveform measurement method described above and the results were compared to positions measured by GPS on the research vessel deploying the light bulbs.

Results

One source of error was drift in clock speed between the DAT recorders. Drift rates between machines were 0.5–2 ms/min. However, drift rate was consistent, and by sending several calibration signals per hour, the rates could be calculated. Based upon these rates, a correction factor was determined for each DAT and introduced into the time delay measurements.

The results of the calibration tests match theoretical predictions reasonably well (Fig. 2). The best localizations are predicted for sounds occurring within the array, while accuracy decreases with distance from the array, especially outside the corners. Of the 30 bulbs dropped during the two calibration sessions, two localizations outside the array were rejected because the localization analysis produced divergent, nonintersecting hyperbolas. Inside the array, the mean difference between the GPS positions of the drop sites and the acoustically determined positions was 68±22 m ($n=10$). Outside the array, mean error was 567±642 m ($n=18$).

Another potential source of error is multipath arrivals of a signal at the buoys. The light bulb implosion data were inspected for this. Several multipath arrivals with monotonically decreasing amplitude were observed when bulbs were imploded near buoys. The arrival times were assumed to occur in the following order: direct path, surface bounce, bottom bounce, surface-bottom bounce, and bottom-surface-bottom bounce. Based upon this assumption, we were able to calculate bottom depth, hydrophone depth, and bulb implosion depth. It was then possible to determine the exact time of implosion. Measured travel times to receivers matched most closely with direct path estimated travel times. The first arrival was at least 10 dB louder, and usually closer to 20 dB louder, than bottom-bounce arrivals, enabling us to ignore bottom bounces in subsequent use with vocalizing animals.

Field deployments of this system around blue whales in the southern California Channel Islands (34° 05′N 120° 00′W) were successful, with buoys proving to be excellent platforms for recording whales' low-frequency sounds. Figure 3 shows the tracks of several vocalizing blue whales. Buoys survived repeated deployments in highly variable weather conditions.

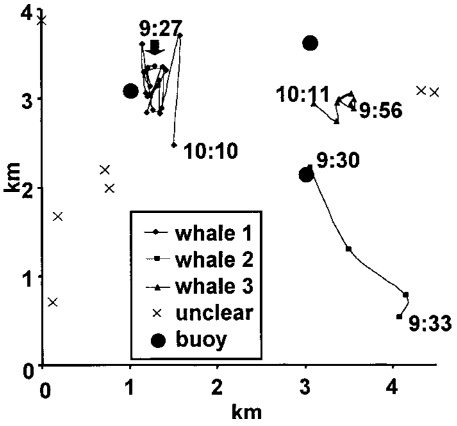

FIG. 3. Acoustic localizations of foraging blue whales recorded on July 19, 1996. Shown here are tracks of signals recorded from three or more animals; times are hours:minutes. Because the localizations for whale 2 are off one corner of the array, they have large range errors (see Fig. 2), and it is likely that the track shown here represents these errors rather than actual whale motion. These signals were attributed to one animal because of the consistent bearing from the array and the short time period between signals. It is also possible that whales 2 and 3 are the same individual, with whale 2 returning to the edge of the array and resuming vocalizations after a period of silence. "×" symbols denote localizations for which it was unclear whether the sounds were produced by whales 1–3 or other individuals.

DISCUSSION

This system was designed as a low-cost, easy-to-operate recording system that could be used for tracking sound sources in the open ocean. The results of the light bulb experiments indicate accuracy to within 60 m inside the array. Outside the array, accuracy is greatly reduced. However, the bearing of signals relative to the array is maintained, providing information that is still useful. The error inside the array compares favorably to the GPS positioning error of approximately 40 m (August *et al.*, 1994) and could probably be greatly reduced through the use of differential GPS transmitters and receivers. Most calculated locations were consistently southeast of drop sites. Another of 10–15-m of error could be associated with the 40-m hydrophone trailing behind the buoys in the northwesterly direction at a 25–50° angle.

Figure 3 is included as practical demonstration of use of the array. During a session in which blue whales were tracked, the array was used to distinguish between several vocalizing whales, allowing at least two pods—probably two individuals—to be tracked in time and space. Tracks were determined by linking successive vocalizations that were nearby in time and space. In addition to showing how vocalizing blue whales move with respect to each other, this information can be compared with data on prey field structure, sighting info, and tracks of tagged individuals (Croll *et al.*, 1998).

The primary advantages to this acoustic tracking system are price and ease of use. These buoys are far less expensive than multichannel signal conditioning and recording systems connected to fixed bottom-mounted arrays or long towed arrays with large tow ships. Another advantage over towed arrays is that after deployment, the research vessel's movements are unconstrained and it is free to perform other functions such as behavioral observations and tagging. In addition, the left–right ambiguity associated with towed arrays does not exist with these buoys. The errors associated with this system in the pelagic environment are not large when compared with the movements of pelagic species. While sonobuoys are sometimes available to researchers without charge, sonobuoy systems still require receivers and multichannel recording systems. In addition, they transmit on regulated frequencies, potentially entailing extra permitting issues. Finally, not all researchers have access to sonobuoys, and those that do could be subject to political changes denying access.

Buoys are advantageous because they may be deployed from small vessels wherever animals are located. The impacts to both the environment and the animals whose behaviors are being studied are reduced through the use of small vessels and recoverable buoys. They have been used in sea state conditions through Beaufort 5. This system is durable, easy to use, and can be deployed and recovered with only two people.

The simplicity of this system makes it feasible for biologists without engineering backgrounds to collect and analyze sound data in new ways. The buoys are easily assembled from commercial off-the-shelf components. Most personal computers now have sufficient memory and hard disk space for the data analysis, and software for the time-alignment and localization steps is available from the authors.

This system may also be deployed as a moored array in the coastal environment, or as time-synchronized recording stations in terrestrial and polar-ice environments. Other studies with better positional accuracy than nondifferential GPS have achieved much higher animal-location accuracy (McGregor *et al.*, 1997; Janik *et al.*, in press). As the array does not move in these environments, increased positioning accuracy is possible, and onboard GPS units would not be required, further reducing cost.

This system has some disadvantages. Unlike sonobuoy recordings, data are not acquired until the buoys are recovered. However, no buoy has been lost in over 50 deployments. Due to DAT tape limitations, recording sessions last only 5 h per deployment, not enough time for some applications. However, retrieving and redeploying the buoys with new tapes may extend this time limit, which takes only slightly longer than the initial deployment time. An alternative solution would be to use an A/D microcontroller computer system with programmable sampling rates and large storage medium.

It is hoped that this system will provide a much larger group of researchers with the acoustic tracking technology necessary to study the movements and other behaviors of marine and terrestrial organisms. By doing so, researchers may be able to gain new insights into questions about social interactions, foraging, population structure, and conservation.

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