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A mobile video/acoustic system for simultaneous underwater recording of dolphin interactions

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Summary

A mobile video/acoustic system was developed that permits real-time synchronous recording of the vocalization and behavioral activities of individual, wild dolphins. Manually operated underwater, the system consists of two omni-directional hydrophones cabled through a custom underwater housing into a stereo Hi-8 video camera. Hydrophone spacing on the housing is scaled to the human interaural distance based upon the speed of sound in water. Location of the vocalizing dolphin is based upon associating visual distribution of animals with directions to sound sources as determined by aural psychoacoustics. Examples of the utility and application of this system are presented for free-ranging Bahamian Atlantic spotted dolphins (*Stenella frontalis*).

Introduction

Significant correlations have been made between behavioral state and types of vocalization of some free-ranging whales and dolphins (e.g. for odontocetes, Sjare & Smith, 1986; Weilgart & Whitehead, 1990; for mysticetes, Clark, 1982, 1983; Tyack, 1983; Silber, 1986; Chabot, 1988). However, descriptions of dolphin social interactions coupled with acoustic emissions have been largely limited to surface observations (e.g. Norris *et al.*, 1985) or have focused on captive individuals (e.g. Tyack, 1986; Caldwell *et al.*, 1990). Information collected from these vantage points may represent only a fraction of the complexity encompassing the social lives of free-ranging dolphins.

Coordinated social organization results from the transmission of information from one animal to another (Smith, 1991). Dolphins live within structurally coordinated social groups, where communication between individuals and groups is likely to be important for the maintenance of social life (Norris & Dohl, 1980; Norris & Schilt, 1988). Recognition of individuals is an important factor for studies of communication; we can identify individual dolphins within groups based upon scars, marks, and unique pigment patterns (Würsig & Würsig, 1977; Würsig & Jefferson, 1990). However, the identification of specific vocalizing individuals has not been possible until recently, and then primarily within groups of dolphins in captivity (Tyack, 1985).

Identification of vocalizing individuals and groups of cetaceans has been facilitated by a variety of sound recording designs; including stationary arrays (Watkins & Schevill, 1974; Clark, 1980; Clark *et al.*, 1986; Frankel *et al.*, 1991, 1993), mobile systems suspended from boats (Sayigh *et al.*, 1993), and electronic devices attached to the animals (Tyack, 1985; Tyack & Recchia, 1991). Stationary phased-array systems (e.g. Clark, 1980) point at vocal groups that were in most cases being tracked by theodolite. Watkins and Schevill's (1974) arrays yield poor spatial resolution except when animals are within or immediately around (<150 m) the array. The arrays designed and employed by Clark *et al.* (1986) and Frankel *et al.* (1991, 1993) permit tracking of individuals. Mobile arrays serve well to coordinate descriptions of visual and acoustic behavior over small areas (<1 km^2) for odontocete species that habitually travel with boats. Attachment devices for odontocetes generally require training and are limited to animals that have been captured. The advent of inexpensive and portable high-resolution videography has made behavioral descriptions of dolphins underwater a relatively easy task. We present here a simple device that provides binaural input, compensated for the water:air sound speed ratio, that allows a person to estimate direction to an underwater sound source from videotaped interactions between dolphins. The system is presently mainly useful for sounds in the human-audible hearing range, especially whistles; and has not been tested with higher frequency clicks, click trains, and whistles above 20 kHz.

Methods

Design of the mobile video/acoustic system

The mobile video/acoustic system, hereafter referred to as the MVA, consists of an audio stereo Hi-8 video camera (Sony model CCD FX710 with an audio recording bandwidth of 20 kHz; any stereo sound video camera can be used) that is linked to two omni-directional hydrophones (each with a bandwidth of 0.14–14 kHz and a sensitivity of − 162 dB re 1 volt). The hydrophones are mounted in a Styrofoam backing to decrease sensitivity to high frequency sounds from the sides and back of the array. They are mounted on 15 mm diameter PVC tubing with a separation distance of 63 cm. This separation is approximately five times the human interaural distance to account for the difference of sound speed in water and air. The hydrophone cables are threaded through the housing back plate to the camera. The PVC tubing is filled with sand for ballast and is mounted to weights on the lower external surface of the underwater housing (Fig. 1). An internal cable links the electronic remote of the camera to the external housing switches: the switches magnetically trigger the camera's internal remote through the cable. The system is portable, weighs less than nine kilograms in air, and is neutrally buoyant.

Calibration of the camera's two audio channels was conducted with a Brüel & Kjaer 4223 Piston phone, a Brüel & Kjaer 8104 hydrophone, and two frequency tones of 250 Hz and 320 Hz of 20 seconds duration. These tones were recorded simultaneously on both audio tracks of the camera. Then, the recorded tones were compared to the original tonal pulses: energy output was within two percent of the expected values for both audio channels. Because there is no input-gain adjustment on the video camera, this calibration provided baseline information (important for the significance of the auditory analyses of recordings from each experiment) on the input gain for each audio channel.

Experimental playback procedure

Experimental playbacks were conducted on the Little Bahamas Bank, north of Grand Bahama Island, Bahamas, and in the swimming pool at Texas A & M University at Galveston, Galveston, Texas. Each experiment consisted of a continuous fifteen minute playback of dolphin and whale sounds using segments eight and nine from side two of the tape *Whales and Dolphins*, produced by The Nature Company, 1993. The equipment used for all

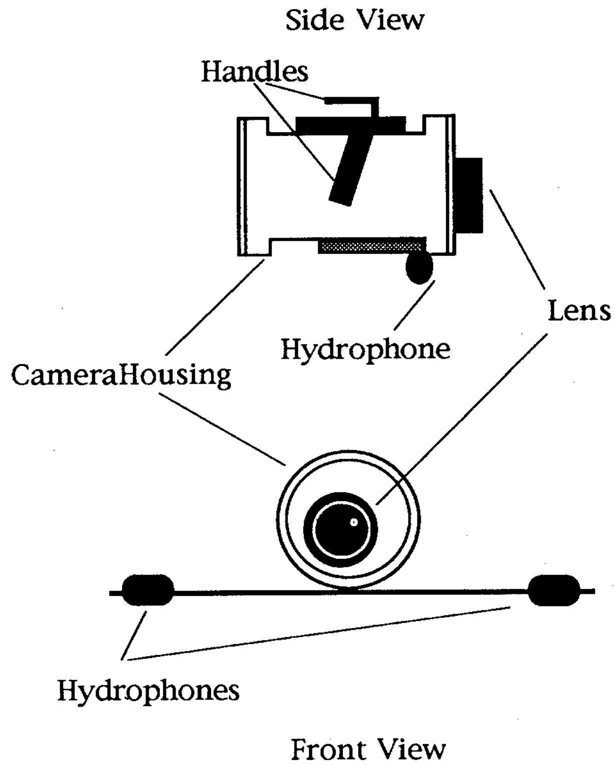

Figure 1. Schematic of the mobile video/acoustic system (1 mm = 10 cm).

playback experiments consisted of two University Sound Speakers (Model UW-30), a Realistic MPA-20 120 V/12 V solid state amplifier and a Marantz PMD-430 cassette recorder. Procedures and equipment were the same for playback tests in the pool, with the deep-end of the pool substituting for the starboard side of the vessel. In the pool, the speakers were lowered to a depth of two meters and were nine meters apart. Acoustic and visual data for each experiment were collected by recording with the mobile video/acoustic system described above. Visual documentation of the MVA orientation relative to the underwater speakers was accomplished with continuous above-water video recording of the MVA's underwater position, and by manually recording the MVA's underwater position with respect to the vessel side at 30 second intervals.

For the vessel playbacks, the two underwater speakers were deployed over the starboard side of the 23 m schooner, R/V *Jennifer Marie*, and lowered to a depth of approximately 3.5 m in water 6 to 7 m deep (Fig. 2). For all experiments, both speakers were used with the playback-channel sequence selected randomly between right, left, or both speakers. For this report, the term 'playback-channel' refers to the speaker (left or right) that projected sounds during an experiment, while 'perceived-direction (PD)' denotes the direction—right, left or both (center)—to a given loudspeaker

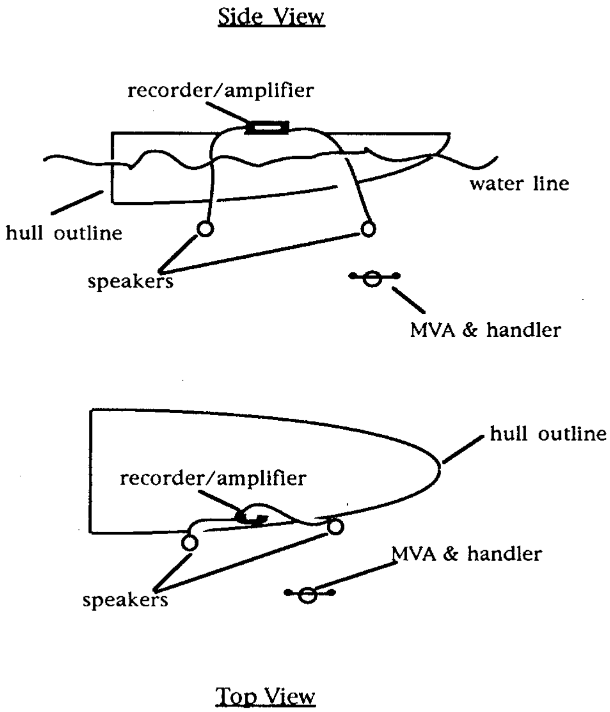

Figure 2. Schematic of Field Playback Experiments aboard the R/V *Jennifer Marie*. (In side view, MVA and handler are at the same depth as speakers, but drawing does not show depth quality. Figures are not drawn to scale. Pool tests set up similarly, see text for details.)

signal as perceived by a human listener listening to the stereo tape during post-experiment analyses. The system handler (SH), unaware of the playback-channel sequence to be used during each experiment, swam at a distance between two and three meters from the boat. The forward face of the MVA (axis of the hydrophone pair) was held in a position either parallel or perpendicular to the speakers as the SH swam in a path parallel to the long axis of the boat. Scheduled changes in the orientation (either parallel or perpendicular to the boat side) of the forward face of the MVA were conducted by the SH at 30 second intervals; however, due to varying water current speeds, the scheduled sampling rate for changes in position was not followed exactly. Therefore, the underwater and surface video recordings of the position of the MVA underwater provided an accurate indication of the orientation of the MVA with respect to the starboard side of the vessel or to the deep-end of the pool. These records ultimately yielded information for determining the expected direction of the loudspeaker source relative to the axis of the right and left hydrophones as recorded on the audio channels of the video camera.

Three independent human subjects acoustically analyzed each playback experiment, by listening binaurally to the stereo recordings, using the same equipment (headphones, stereo Hi-8 camera) as originally employed for data collection during the experiments. Each subject noted the perceived directions for each of the approximately 30-second playback segment of an experiment. A pooled-average, percent-correct test statistic was employed for comparison between the expected and the perceived-directions (PD), as noted by three independent observers, to estimate accuracy and reliability of the system (C. E. Gates, Texas A & M University, pers. comm., 1993). The expected PD was determined by examining the surface video, the playback-channel, and the identified relative underwater orientation (parallel or perpendicular) of the MVA system for each experiment.

The sequence of and total number of different perceived directions to the speaker source were compared between the three observers. Consistency in the sequence of the perceived directions between observers was examined with Kendall's coefficient of Concordance (Lehner, 1979). The Kendall's coefficient (W) test was conducted on the data for each experiment; then, an average coefficient of concordance was taken for all pooled sets.

System application with dolphins

The mobile video/acoustic system was used to record dolphin vocalizations and behavior during swims from 15 May to 23 September, 1993. A 'swim' was defined as a person being in the water for three minutes or more with dolphins in visual range. This study group of Atlantic spotted dolphins (*Stenella frontalis*) is found in Bahamian waters, and generally travels in small groups of one to ten individuals (Byrnes *et al.*, 1989). The study group, resident to the Little Sand Banks north of Grand Bahama Island, consists of at least 85 recognizable individuals. These spotted dolphins were observed because of their tolerance of human swimmers—they have regularly swum with snorkelers and divers for the past 25 years—and because of the clarity of Bahamian waters (Byrnes *et al.*, 1989).

There were 83 swims in 1993. During 20 of these, 234 minutes of observations were recorded with the MVA. Preliminary acoustic analyses were performed on four swims for 51 minutes of data on dolphin behavior and vocal activity.

Results

The MVA system was field-tested with sound playbacks of cetacean vocalizations from both captive and field situations. A total of six trials (labeled A through F) of the experimental design were instigated for both the pool and the field tests. The high degree of noise from snapping shrimp and shallow

Table 1. A limited presentation of the use of Pooled-Average Percentages and Kendall Coefficient Ranks for data collected to examine inter-observer reliability of audio tape analyses, as well as accuracy measures for the MVA for indicating direction to a sound source

Experiment 'B'						Experiment 'E'					
	PD subset						PD subset				
Time	Obs No. 1	Obs No. 2	Obs No. 3	EPD	%C	Time	Obs No. 1	Obs No. 2	Obs No. 3	EPD	%C
10:38:40	B	L	R	R	33	10:38:50	L	L	L	L	100
10:39:17	L	L	L	L	100	10:39:30	B	R	B	R	33
10:39:42	R	R	R	R	100	10:39:52	R	R	B	R	66
10:40:05	B	B	B	B	100	10:40:39	B	B	B	B	100
10:40:40	L	L	L	L	100	10:41:04	B	R	R	R	66
10:41:30	B	B	R	B	66	10:41:35	B	B	B	B	100
Pooled Average %C: 83%						Pooled-Average %C: 77%					

	PD totals				PD totals		
	L	R	B		L	R	B
Obs No. 1	2	1	3	Obs No. 1	1	1	4
Obs No. 2	3	1	2	Obs No. 2	1	3	2
Obs No. 3	2	3	1	Obs No. 3	1	1	4

	Kendall's Coefficient Ranks				Kendall's Coefficient Ranks		
	L	R	B		L	R	B
Obs No. 1	2	1	3	Obs No. 1	1.5	1.5	3
Obs No. 2	3	1	2	Obs No. 2	1	3	2
Obs No. 3	2	3	1	Obs No. 3	1.5	1.5	3

Key: Obs=observer, EPD=expected PD, %C=percent correct, L=left PD, R=right PD, B=both (center) PD. Note that the values listed are only a sub-set of the data points for both experiments. Therefore, the pooled average %C values here are not the values listed for the experiment as a whole. This same principle applies to the ranks presented in the lower portion of this table.

water (two meter depth) caused interference on recordings during experiment 'D'.

Inter-observer reliability

A comparison of the total number of PDs recorded by the three independent observers yielded an average Kendall's Coefficient of Concordance of 0.58. Two experiments ('C' and 'D') contained poor signal to noise ratios due to shallower water, the background noise of snapping shrimp in the recording area, and a loose connection in power supply wiring. Thus, when equipment is functioning correctly and levels of background noise are reduced, the average Kendall's Coefficient of Concordance is 0.82. Concordance values ranged from 0.11 to 1.00 for the six experiments.

The Kendall's Coefficient of Concordance was used as a measure of the consistency and reliability between the three observers for their detected changes in the PD of the sound source recorded with the MVA system. Ranks ranging from one to three were assigned to the total number of the left, right, and center PDs. Comparisons between the number of possible PDs for the three observers provided a suitable database for examination of inter-observer reliability. Limited examples of the 'raw data' from the three observers and the resulting ranks for experiments B and E are presented for clarification of analysis methodology (Table 1). Results indicate that good reliability between observers was possible. For experiment B, while a concordance value of 0.49 seems low, two observers matched ranks exactly; thus, this value was considered acceptable. Concordance values for experiments C and D are also low and are due primarily to equipment noise and electrical grounding problems, respectively.

A pooled-average, percent-correct statistic was calculated by comparing values from each observer's results with the expected-PD from within each 30 s time interval (Table 2). Percent-correct values were either a 0%, 33%, 66%, or 100% depending on the number of correct matches between the three observers and the expected analyzed channel (Table 1). The percent-correct values for each 30 s time segment within each experiment were averaged to yield the pooled-average, percent-correct test statistic, and these

Table 2. Pooled-Average percent-correct data

Experiment	Pooled-Average Percent Correct
A	85%
B	79%
C	84%
D	75%
E	83%
F	80%
Average of values for each experiment:	82%

The expected PDs were compared with the observed PDs and then pooled and averaged. The averaged percents correct of these pooled averages are presented below.

indicate the reliability for determining general sound source locations (left vs. center vs. right) with the MVA for each experiment. The mean for these pooled averages was 82% (Table 2), indicating a high degree of concordance between the perceived direction to the sound source and the actual position of the loud speaker.

System use with dolphins

During preliminary analyses of 51 min of recorded swim time, 204 whistles were detected: of those, approximately 37.7% could be attributed to a specific dolphin. The remaining 62.3% of the whistles could not be assigned to a certain individual either because a whistle was recorded when no dolphin was within the camera viewfinder, or the dolphins were too close to one another for source resolution with our system.

Discussion

We have described a mobile video/acoustic system designed to simultaneously record dolphin vocalizations and behavior, permitting determination of the general direction to a sound source and identification of vocalizing individuals. Results from controlled playback experiments indicate that the system does provide general information on the direction to a sound source and the identification of vocalizing dolphins within view of the camera lens. Examples from the encounter data collected on spotted dolphins demonstrate that this system can provide information to facilitate identification of vocalizing dolphins. Correlation between vocalizations and specific behavioral units of dolphins underwater is now possible with this recording system.

While this system can help provide data to permit examination of the intricacies of dolphin acoustic and visual behaviors underwater, there are still a few constraints that need to be addressed. This system's mobility allows the handler more freedom of movement during encounters with dolphins; however, the swimmer is still required to surface to breathe and his/her ability is limited by swimming ability.

Initial placement of the hydrophones on the dorsal surface of the camera housing yielded recordings with a high level of water noise during pool and field tests. Since the camera operator spends at least 60% of a dolphin swim encounter near or at the water surface, the dorsal surface of the housing has a higher probability of breaking the air-water interface than when it is mounted lower on the housing. This causes water noise to be recorded on tape and to mask dolphin vocalizations. Repositioning of the hydrophones to the ventral surface of the housing decreased the noise caused by the air-water interface.

Bubble noise was created from snorkels when swimmers submerged; this noise was most significant on the recordings when the system handler dived. This problem can be solved by at least two modifications: high-pass filters to decrease low frequency bubble noise, and having the handler hold his/her breath while snorkeling below the surface. Bubble noise from the hydrophone PVC tubing was reduced greatly by filling the tube with sand and sealing the ends. The sand provided additional ballast to the front end of the housing, thus keeping the lens and hydrophones further away from the water-air interface and allowing the swimmer to concentrate more on the study subjects.

Noise from vibration of the hydrophones against the Styrofoam holders was noticed during analysis of recordings made when encounters occurred while surface-water currents were 0.33 m/s or greater. Better attachment of the hydrophones to the Styrofoam holder will probably decrease this vibration noise.

It is apparent from these binaural analyses that general direction to the underwater sound source can be determined. The spacing (63 cm) between the hydrophones is scaled to account for the approximately fivefold increase in the speed of sound in water. Direction to vocalizing individual dolphins is facilitated when dolphins are separated and in view on the video screen. Error in identification of the vocalizer could occur if dolphins are spaced within two body lengths of each other, or if the vocalizer is out of view of the camera but in the same direction as an animal within the field of view. By analogy to radio-tracking of animals, there exists an error polygon for source detection (Mech, 1983). Within this error region, it will be possible to determine the general direction to a sound, but not to pinpoint an individual location of origin. This error is caused by human discrepancies in direction determination, as well as by physical limitations of the system and by complicated sound paths in shallow water. Judgment decisions are a part of the human analysis of the recordings. On land, as sound frequency increases, the ability of the human ear to judge direction decreases; for example, at 125 Hz the error is roughly 10° while at 2–5 kHz the error is 20° (Pierce, 1901). At higher frequencies, we get better at direction determination but are aided by our external pinna in doing so. This is not helpful underwater, unless one builds scaled pinna (K. S. Norris, pers. comm.).

Another potential for error in determination of vocalizer identification is that of the sectioning of the video screen, and matching those screen sections with the auditory differences observed. By ear, humans can section what we hear into left side, right side and center. But if we also section the video screen into left, right and center, can we be certain that the auditory sections and the visual sections indicate the same areas? And, is this sectioning to the left, right and center good enough for biological resolution? Furthermore, what numerical values should we give to each section; that is, how big should each section be? Or should the sections vary with the given recording? These are questions we will answer with future tests of our mobile video/acoustic system. With future tests, we will also evaluate the sensitivity of the system and of the human observers for determining direction to a sound source.

While there is variance in our ability to determine the direction to an underwater sound source, we are still able to gather valuable underwater observations on the acoustic and visual behaviors of dolphins. As shown by our preliminary results from dolphin recordings, we can attribute about 37% of the recorded and counted whistles to a particular individual. Our determination of a sound source's direction is not resolved to a point source but instead yields a general sector of space from which the sound originated. In any case, it is almost impossible to identify the specific individual producing a sound when the dolphins are grouped tightly or when no individual is present within the camera viewfinder. However, in some cases, as we learn more about the coordination between acoustic and visual cues, identification of the vocalizer may be facilitated by behavioral or contextual information.

As an example, dolphins have been observed emitting bubble streams when vocalizing (Johnson & Norris, 1986). Better understanding of the association between vocalizations and bubble streams may enable us *a posteriori* to identify a vocalizer within a group of tightly-spaced dolphins. The duality of our system, through simultaneous but independent video and sound recordings, provides a method to determine sound source direction with behavioral and contextual information. In short, we can use our perceived arrival time differences of a signal to estimate the direction to a sound source. Then in ambiguous situations, the use of contextual information and identified sound characteristics may indicate which individual is vocalizing.

Early studies of dolphin communication were hindered because researchers were unable to identify vocalizing individuals within a social grouping (Evans & Bastian, 1969; Herman & Tavolga, 1980). Communication is probably the single most important defining factor in social life. By employing our newly-developed mobile video/acoustic system, it will be possible to record dolphin vocalizations during different behavioral contexts and to identify the vocalizing animal in at least some free-ranging dolphin groups.

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