DESIGN FOR A MANATEE FINDER: SONAR TECHNIQUES TO PREVENT MANATEE-VESSEL COLLISIONS

FINAL REPORT ON PURCHASE ORDER S-7701-617591

PREPARED FOR

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Preface

This project was funded by the Florida Fish and Wildlife Conservation Commission, Florida Marine Research Institute (Purchase Order S-7701-617591) under the Manatee Avoidance Technology Program. Experimental studies of manatees at SeaWorld of California were authorized by a permit from the U.S. Fish and Wildlife Service, Division of Management Authority (MA054026-0) issued on 12/4/02. The work was conducted by biologists from Hubbs-SeaWorld Research Institute (Dr. Ann E. Bowles, Tina Yack) and sonar technology experts at the Scripps Institution of Oceanography (Dr. Jules S. Jaffe, Fernando Simonet). The Animal Care Staff at the Manatee Rescue Facility at SeaWorld of California provided access to the research subjects and safety monitoring during experiments.

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Introduction

In 2001, the Florida legislature appropriated funds for research to find methods of reducing manatee-boat collisions by means of technological solutions, the Manatee Avoidance Technology (MAT) Program. The present project was funded by the Florida Fish and Wildlife Conservation Commision, Florida Marine Research Institute (FMRI) under this program. Its goal was to determine the feasibility of using sonar techniques to detect manatees in shallow water. The ultimate goal will be to develop a 'Manatee Finder' to detect manatees at ranges suitable for warning boaters of their presence.

When a boat approaches a manatee, two individuals determine the outcome of the interaction – the manatee and the boat operator. Although it is tempting to focus on the responses of manatees as a possible solution to collisions, there is a substantial literature on wildlife-vehicle collisions in the terrestrial environment showing that warning devices do not reduce the incidence of animal-vehicle collisions (Romin and Dalton 1992, Romin and Bissonette 1996, Ujvari *et al*. 1998, Danielson and Hubbard 1998). The collisions result from a mismatch between species-typical defensive behaviors and effective avoidance responses. Effective strategies for preventing collisions in terrestrial animals include 1) warning the driver, 2) reducing speed limits, and 3) building structures that reduce the probability of interaction at frequently-used crossings (e.g., Garret and Conway 1999, Lehnert and Bissonette 1997).

Empirical data on marine mammals, including manatees, are consistent with the terrestrial animal literature. Manatees have been observed turning and swimming into deeper water at distances of several hundred meters during vessel approaches (Nowacek 1999 and unpub). The response was probably evolved as a defense against terrestrial predators, but is not effective against vessels. If boaters could be warned in time to prevent collisions, manatee-vessel interactions could be prevented regardless of the appropriateness of manatee responses. Under MAT funding, we have begun testing sonar as a tool for detecting manatees reliably.

Based on target strength measurements of other large marine animals, good sonar returns were expected from manatees at ping frequencies between 10 and 80 kHz (Au 1996, Bertrand *et al*. 1999). Several previous efforts had attempted to detect manatees using sonar (Matzer and Associates 1980; Fletemeyer 1982, American Dredging Company 1983; Kinnaird 1983; Dickerson *et al*. 1996). These efforts were limited in scope and none measured manatee reflectivity quantitatively. Some reported good sonar returns and detections, but others cited scatter from surface and bottom, sonar shadowing, high background noise levels, vessel-generated turbulence, and low-amplitude returns as reasons for limited success. Dickerson *et al*. (1996) tested commercial fish-finding sonars. They obtained good returns from air-filled floats in a test pool, but poor returns from live manatees. These authors explained the poor returns in live animals by speculating that manatee blubber 'attenuated' high-frequency echoes.

Based on the previous efforts, it seemed likely that pings at lower frequencies and relatively high levels were likely to yield the sonar returns needed to develop the Manatee Finder. However, from the perspective of preventing harassment, frequencies outside the manatee range of hearing were desirable. Therefore, experiments on manatee responses to audible pings were conducted before the start of the reflectivity experiments to determine the level at which avoidance or other behavioral evidence of discomfort was likely to appear. Previous experiments conducted at HSWRI (Bowles *et al*. 2001) had shown that manatees did not respond with aversion to 10-80 kHz tone pips from a Dukane/Netmark 1000 pinger producing 300 ms peeps at 4 s intervals. Most of the energy in these pings lies in the 10-40 kHz range, at the mid- to high-end of the manatee's hearing range (Gerstein *et al*. 1999) and they produce levels of approximately 130 dB re 1 uPa RMS SPL. Responses at greater levels were measured during the initial stages of the present project.

Once the tolerance limits of the manatees had been identified, target strength measurements were designed and conducted, as described in the 'Methods' section below. The goal was the design of pings that could be used to detect manatees at ranges of at least 100 m without causing avoidance responses. Secondary goals were to determine the effect on sonar returns of shallow water conditions and bubbles produced by boats.

METHODS

Subjects and experimental area

Five rehabilitated male manatees (**Table I**) were tested in the main pool of the Manatee Rescue exhibit at SeaWorld San Diego. The test pool was dumbbell-shaped with dimensions 33 m x 10 m x 3 m (at widest area), with a volume of 860 m^3. For the purposes of quantifying usage patterns, the 'dumbbell' was broken up into three sections (**Figure 1**). Section 3, located at the western end of the pool, contained the transducer cage. Section 1 was at the eastern end, and contained an object that the manatees could manipulate as a toy. The toy was composed of a cage of approximately the same construction as the transducer cage. It was deployed and retrieved using a float line and float. It was placed in the pool to provide the manatees with an object to manipulate at both ends of the pool, preventing them from manipulating the transducer cage persistently throughout experiments. Section 2 formed a channel between Sections 1 and 3.

The test pool also housed a collection of large South American fish, including arapaimas, arawanas, alligator gars and pacu. These fish occasionally interacted with the manatees or came into the field of view of the sonar; however, the fish normally stayed near the bottom of the pool and did not interfere significantly with the experiments.

Video data collection

Signals from two overhead cameras and a camera lined up with the axis of the sonar beam were recorded by an ATV Falcon 4-channel Digital Video Recorder (DVR)(**Figure 2**). The fourth channel recorded a time code from the sonar equipment to ensure that animal orientation could be collected ping by ping. During all trials, a two handheld video cameras were positioned in the

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Table I. Summary of manatee age, weight, and condition. Data provided by SeaWorld Animal Care Department.

Name	Condition at Arrival	Weight (kg)	Age (yr)	Condition
Eddie	Found stranded, 2000	546	9-10	In good health
Lil' Joe	Found as orphan in Halifax River, 1989	694	11-12	In good health
Slip	Captive-born, 1991	441	9	In good health
Vail	Struck by boat on the Indian River at Titusville, 1996	587	5+	Paddle has propeller scars, large section missing on left; otherwise healthy
Webster	Captive-born, 1991	689	9	In good health

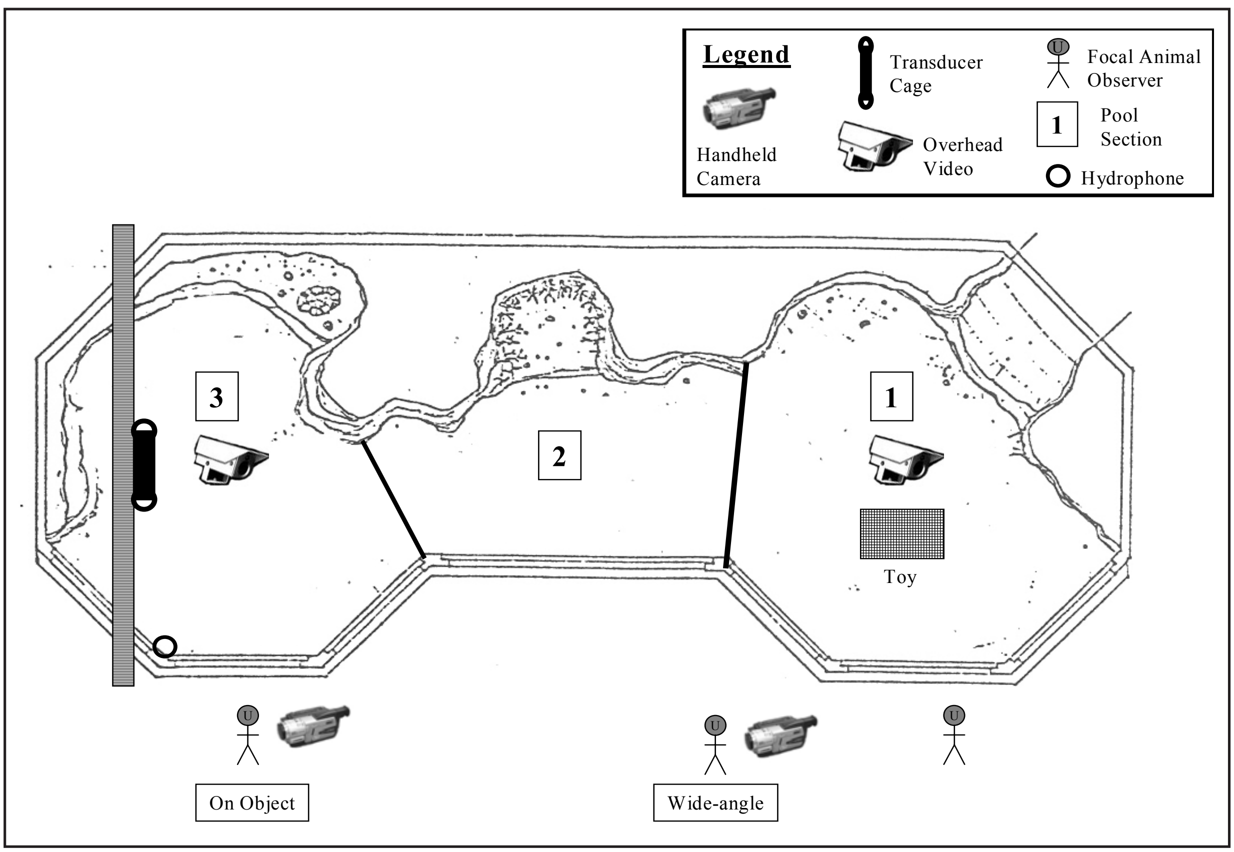

Figure 1. Diagrammatic view of Manatee Rescue facility with observer and camera locations, location of the overhead walkway and transducer cage

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Figure 2. Three-channel image collected by the digital video recorder. Top left: camera view along beam of 171 kHz transducers. Top right: Section 1 and east end of Section 2. Bottom left: Section 3 and west end of Section 2.

visitor observation area, looking through a large acrylic viewing panel. Data from these cameras were used to monitor manatee interactions with the transducer cage and the toy.

Behaviors were collected in real time and from video using Handspring Visor Neo Portable Digital Assistant (PDA) units running a custom-designed database (Pendragon Forms 3.2). Focal animal sampling was used to score behaviors of each manatee (Altmann 1974), with each behavior defined using a formal ethogram (**Appendix A**). Two to three individuals were followed as focal animals during experiments to ensure that evidence of distress or avoidance could be identified quickly. Data for the remaining individuals were taken from video. Counts and durations of behaviors, time spent close to and in contact with the objects, and time spent in each Section of the pool and in the water column were quantified. Activity states and location in the pool were also taken from the overhead video.

Audio data collection

Underwater audio recordings were collected simultaneously during all experiments to measure the output level of audible pings and vocalizations of manatees. These were collected with an omnidirectional ITC 6050C hydrophone connected to custom-built power supply with an internal calibration signal. Data were recorded onto a Sony TCD-Pro II DAT recorder.

Audio data were digitized by downloading data directly to digital format from the Sony DAT. They were analyzed in Spectra Plus Pro. The sound pressure level (RMS SPL) and sound exposure level of a sample of pings was collected for each trial to ensure that signals approximated the stated level for the exposure condition and to allow the total exposure during each trial to be estimated.

Behavior data reduction and analysis

Behaviors were broken up into mutually-exclusive categories: (1) activity state (swimming, resting, etc.), (2) pool usage, (3) behaviors in the vicinity of the object, and (4) behavioral events that related to responses (e.g., touching an object). Events were quantified by counts over the period of the trial (number occurring per unit time); states were quantified as a percentage of the total duration of the trial (i.e., behavior or activity per unit time). Behaviors in different categories could occur simultaneously, such as swimming and socializing.

Interactions with the object were quantified in detail. Portion of the body contacting the object, type of manipulation, and time spent closely approaching (coming within 0.5 body length) or touching the object were quantified for each focal animal.

Playback of 10 kHz pings

Audible stimuli (10 kHz) were projected with an ITC 1001 transducer. The transducer cage was

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mounted on an overhead walkway in the center of Section 3 at a depth of 2 m, approximately half the depth of the pool. The 10 kHz stimuli were 50 ms pings projected at a rate of 1/s. Pings with RMS SPL between 130 and 180 dB re 1 μPa were projected in 10 dB increments. A target duration of 15 min per trial was used. Recordings with the DAT system were collected throughout each trial.

The ITC hydrophone could not be deployed in the water column without constant interference by the manatees. It was placed in a 10 cm PVC pipe bolted to the facility wall (**Figure 1**). The pipe was perforated by many 1.5 cm holes to reduce the effect of the pipe on the level of sounds in the frequency range of interest (below 20 kHz) as much as possible.

Calibration of sonar equipment

Although no strong evidence of distress was observed (behaviors will be described under 'Results' below), initial experiments in the SeaWorld pool indicated that manatees reacted to 10 kHz pings, especially at levels that would have been required for the target strength measurements. Therefore, target strength measurements were conducted at a frequency well above the hearing range of the manatee (171 kHz)(Gerstein *et al*. 1999). At this frequency, sonar reflections above the noise level in the pool could be obtained from the manatees at fairly close ranges (1 – 4 m), but not at greater ranges.

At these ranges, traditional sonar target strength measurements could not be made for two reasons. First, the manatees subtended only part of the field of view of the sonar. Strictly speaking, the concept of target strength is only applicable to an entire animal, so the methodology had to be modified to permit quantification of reflectivity given data returned from only part of an animal. Second, sonar measurements were being made in the near field of the sonar transducers, where reflections tend have unpredictable and rapidly-varying levels (for an explanation, see Au 1993). The typical relationships that govern spherical spreading do not apply in the near field. Thus, traditional relationships between measured source and received level could not be used in the estimation of target strength.

In fisheries sonar, the most popular technique for calibrating a sonar system involves the use of calibrated spheres. In a typical application, a sphere (an omnidirectional scatterer) of known reflectivity and therefore computable target strength is positioned at various 3-dimensional locations in the field of view of the sonar transducer(s). The system response (output voltage of the system relative to input voltage from the echo) is measured for each location. These values are then used to calibrate the system by adjusting the settings on the instruments to get a known response. Knowing the settings for each position in the array allows reflectivity from any target in the three dimensional field of view of the system to be estimated even when direct measurements cannot be made. From the reflectivity value, target strength can be inferred.

The procedure for the manatee experiments was based on this protocol. However, the exact reflectivity of a manatee located in the sonar's near field was more difficult to judge because the

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field varied more as a function of manatee position than in the case of a small, static sphere. The problem was solved statistically. The upper limit of a series of reflections was used to estimate the maximum reflectivity of the manatees, with the understanding that a small maximum number indicated a small actual target strength.

During calibration measurements, sonar signals were projected from two sidescan-like transducers (beam patterns of approximately 20º by 1º)(**Figure 3**) mounted at right angles to one another in a protective cage (**Figure 4**). The result was a narrow beam that could be focused on the test sphere, eliminating echoes from other reflective surfaces, such as the pool surface, bottom, or walls. The transducers were operated at a frequency of 171 kHz. They were oriented at right angles to each other so that the intersection of the projected and received beams was relatively narrow, giving the system a small field of view. A video camera was placed in a waterproof housing and mounted so that its field of view was oriented almost exactly along the axis of the combined transducer transmitting and receiving beam.

The video camera and sonar transducers were calibrated together by translating a 38 mm tungsten carbide sphere (target strength [TS] = - 39 dB @ 171 kHz) in a test tank located at SIO. The sphere was translated in two dimensions at several ranges while both video images and sonar reflections were recorded. **Figure 5** shows the effective beam pattern of the sonar, as measured at approximately 100 points in the field of view of the system over which the data were recorded (ranges of nn, nn and 2.6 m). At very short range, 1 and 2 m, the near field sound pattern was quite complicated (**Figure 5a, b**). However, at 2.6 m (**Figure 5c**), the field approached a more interpretable sound pattern. At this and greater ranges, received levels could be estimated from the calibration measurements.

In order to map the absolute 3-dimensional position of the sphere to the field of view of the video camera, a set of image processing programs were written. The image processing algorithms were quite successful at obtaining the position of the sphere from low contrast optical data, simplifying the processing of video data collected with the measurements of reflected level. When calibration was complete, the voltage of the reflection from the sphere could be predicted as a function of absolute 3-dimensional position accurately.

The calibration curves from data collected with the sphere at 2.6 m were extrapolated to a slightly greater range (4 m) for use on manatee data from the SeaWorld pool. Since a range of 4 m was still in the near field of the system, spherical spreading could not be used to estimate reflectivity. A computer simulation was written to model the two-way spreading that the sound underwent for an object at 4 m range relative to the farthest calibrated sphere measurement at 2.6 m. At this range, simple 1/range (1/R) spreading appeared to model the loss best. A 1/R spreading loss was therefore applied to estimate the system's output voltage at 4 m, extrapolated from the 2.6 m data.

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Figure 3. 171 kHz transducers and video camera.

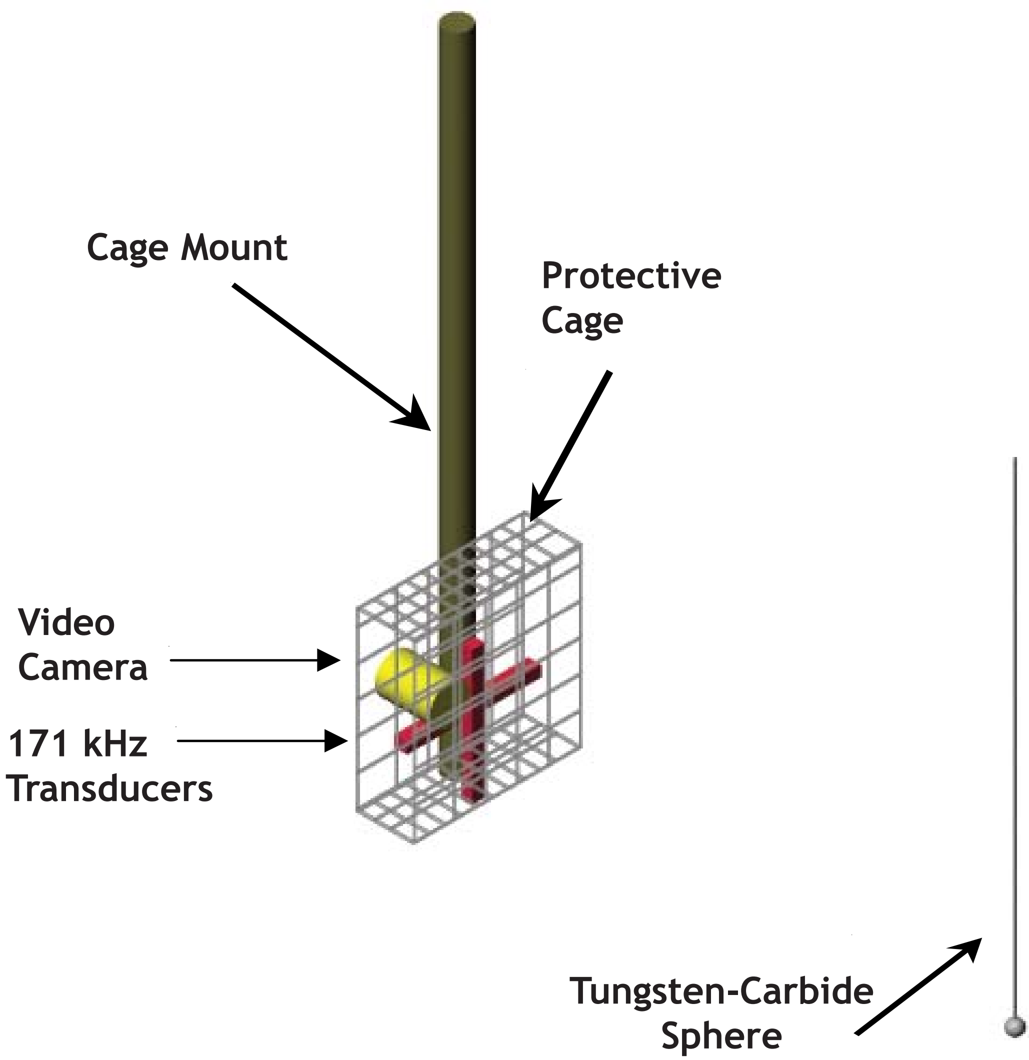

Figure 4. Setup of equipment for calibration procedure and manatee reflectivity experiments.

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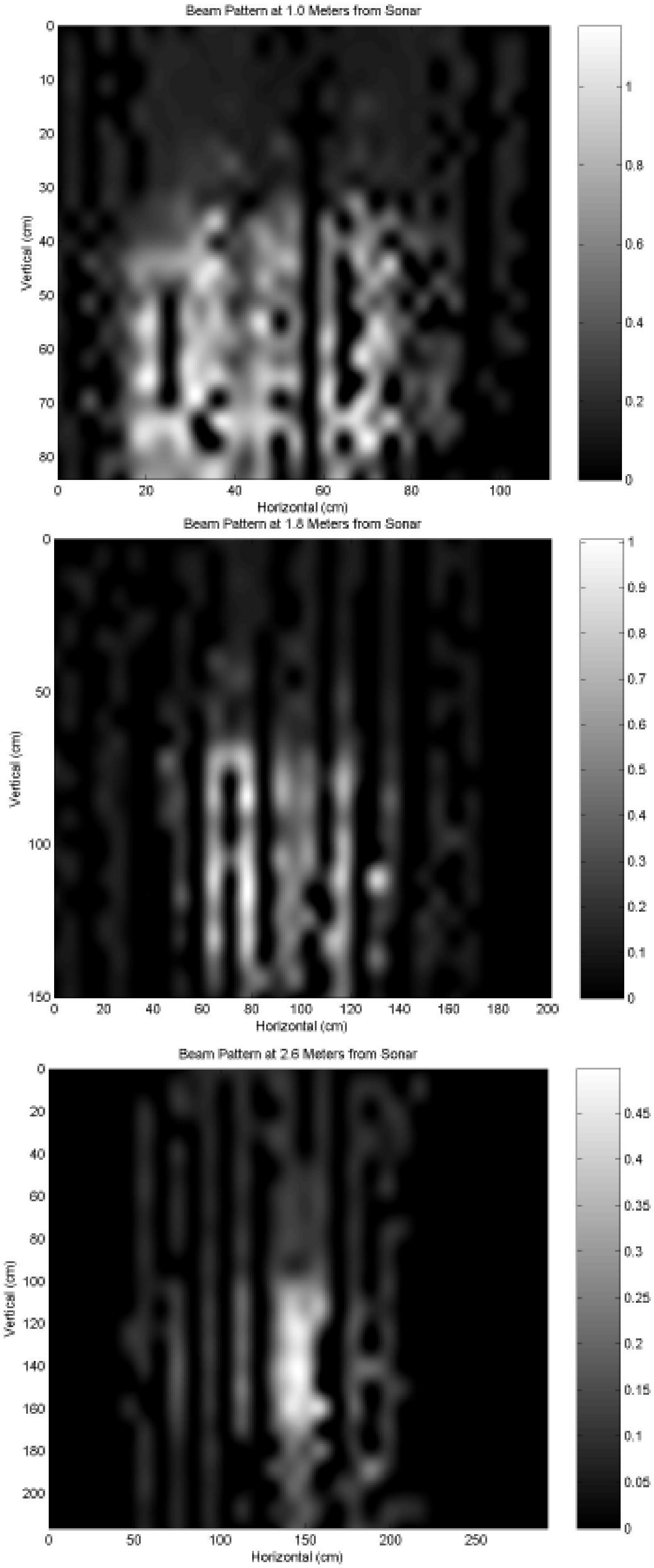

Figure 5. Beam patterns of the transducers at (A) 1 m, (2) 2 m, and (3) 3 m.

Experiments

Baseline observations. In order to compare behaviors of manatees in the absence of the object with behaviors in its presence, baseline observations were conducted. During baseline periods, the manatees were simply observed in the presence of the test cage and toy. The baseline observations were designed to quantify normal behavior patterns and determine typical usage of pool sections. The baseline observations were compared with similar observations made in the presence of 10 and 171 kHz sonar signals.

Experiments with 10 kHz pings. All trials were conducted in the morning, between 0730 and 1100 hrs. The manatees normally received a small feeding at 0630, but little food remained by the time the object was introduced. The major feeding of the day was delayed until after the experiments on most days. Thus, trials were conducted with little or no food present.

The 10-kHz trials were designed to measure the threshold for harassment for short pings. If a high enough threshold of response could be found, sonar target strength measurements could be conducted at frequencies audible to the manatees. Otherwise, negative responses would be prevented by using sonar frequencies well above the manatee range of hearing.

During experiments, levels were increased in 10 dB increments. Manatee behaviors were monitored continuously during exposures to look for evidence of distress, including rapid swimming, thrashing of the body or paddle, and spinning while swimming. If evidence of distress was detected, the stimulus was stopped and a level 10 dB lower was projected.

Animal care staff remained at the poolside throughout the entire trial and assisted with the placement of sonar equipment and the manipulandum. Staff members had the authority to enter the pool to assist an entangled manatee or terminate a trial if the manatees appeared to be in difficulty.

Exposure trials with the 10 kHz pinger were conducted in 1 – 2 hour blocks, one per day over a period of three days (**Table II**). Trials at a given level were planned to last approximately 15 min. The block of trials started with the introduction of the transducer cage, followed by a 15 min baseline observation. The sonar was then turned on and up to six 15-min trials with audible pings were conducted. The first exposure to any given level was always the result of stepping up by 10 dB from the previous highest level. When manatees had shown no response, larger jumps were sometimes used to ensure that all trials could be completed within the number of exposure days allowed by the permit for the project.

During all trials, a manipulandum (a 'toy') was placed in Section 1 to ensure that manatees were not attracted to the sonar cage because it was the only novel manipulable object in the pool. The toy was a simulated crab pot with a float that the manatees had manipulated extensively previous experiments (Bowles et al. 2001). The object was placed in the pool at the same time the as the sonar cage.

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Table II. Summary of trials conducted with 10 kHz pings and 171 kHz sonar signals. Locations refer to the pool section where the object was placed.

Date	Sonar	Level	Sonar Location	Sonar Exposure (hrs)	Toy	Toy Location	Toy Exposure (hrs)
3/13/03	10 kHz	-	2	1.25 (no stimulus)	No	-	0.00
3/18/03	10 kHz	130-150 dB	3	1.64	Yes	1	1.30
3/19/03	10 kHz	140-170 dB	3	1.66	Yes	1	1.92
3/20/03	10 kHz	140-180 dB	3	1.49	Yes	3, 1, 2	1.50
4/1/03	171 kHz	171 dB	3	1.69	Yes	1	1.89
4/10/03	171 kHz	171 dB	3	1.31	Yes	1	1.64
4/22/03	171 kHz	171 dB	3	1.91	Yes	1	1.69
4/24/03	171 kHz	171 dB	3	1.97	Yes	1	2.03
6/24/03	171 kHz	171 dB	3	1.82	Yes	1	1.27
6/26/03	171 kHz	171 dB	3	1.92	Yes	1	1.10
6/30/03	171 kHz	171 dB	3	0.92	Yes	1	1.60

In addition to real-time monitoring during the trials to look for evidence of short-term distress responses, more subtle responses were sought by analyzing video data after the trial. Response measures included 1) percent time in contact with the transducer cage, 2) latency to avoid the sonar cage for more than 5 min (time from the start of the trial to movements to the opposite end of the pool), and 3) percent time spent in each section of the pool.

Sonar reflectivity measurements. The sonar setup was mounted in a protected cage to ensure that the manatees could not harm themselves or the equipment. The signals were short pings consisting of 20 cycles at 171 kHz emitted every 250-500 ms (0.1 ms duration, at a rate of 2 – 4/s)(**Figure 6**). The emitted level was slightly below the maximum allowed by the permit for the study. Ping level at 1 m from the sonar transducers was 171 dB re 1 µPa RMS SPL.

Data from approximately 100 reflectivity measurements were collected. The analysis took place in several stages. First, the capability of the system to detect targets in a reliable manner was tested by establishing a threshold for the sonar reflections. All reflections over this threshold were considered to be returns from manatees. The concurrent video images were examined and manatees were present in the field of view of the sonar system at the appropriate range when reflections above the threshold were measured. Therefore, although the noise level in the tank

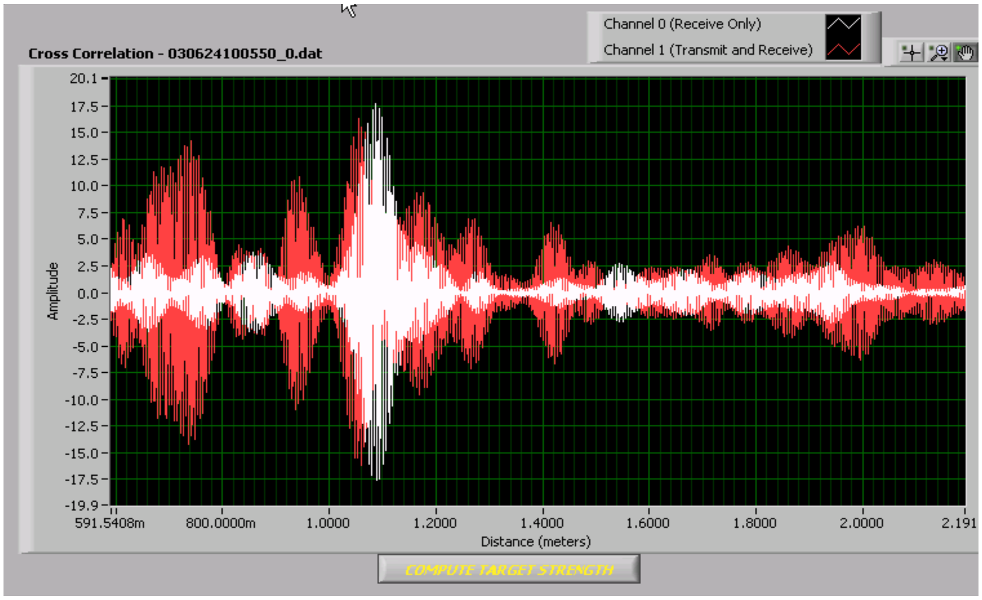

Figure 6. Example of projected ping (red) and returning echoes (white, red) recorded from the 171 kHz transducers.

was high, reflectivity from the manatees at ranges out to 4 m was high enough to permit unambiguous identification. Next, the video images were visually inspected to determine the section of the field of view of the sonar that the target manatee was subtending. The chosen dataset included returns ranging from partial to total coverage of the field of view. Calibration data were then used to identify the most sonically reflective region within the field. Finally, a measure of relative reflectivity was computed by taking the ratio of the reflectivity of the tungsten carbide calibration sphere at that point to the voltage of the sound reflected from the animal. This was used as an estimate of target strength in dB. Taking the most reflective point in the field of view resulted in an extremely conservative estimate of the animal's target strength. Other, less reflective, areas would have yielded a higher ratio and therefore a higher inferred target strength for the target manatee.

Results

The trials conducted during this study are summarized in **Table II**. Responses to 10 kHz pings were measured on three days in March 2003. Trials with the 171 kHz sonar transducers were conducted during six days April and June 2003.

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Experiments with 10 kHz pings

Exposures. **Table III** lists the sequence of exposures during the trials with the 10 kHz transducer. **Table IV** lists the total manatee-hours of behavioral observations collected in each stimulus condition.

Behavioral responses. When the transducer cage was first introduced into the pool on 3/13, the manatees swam toward it immediately. They mouthed the cage and the metal pipe uprights, pushing their oral disk and/or flipper through the space between the pipes and the cage (**Figure 7**). Occasionally, they pushed the cage assembly hard. They manipulated the cage persistently throughout the initial trial, leaving it only for brief periods. The toy was not present in the pool during this trial.

A second series of trials was conducted on 3/18. During these, the manatees received both the cage and the toy. Manatees approached and touched the toy persistently. Initially, it was novel relative to the transducer cage, as the manatees had not been exposed to this object since 2002. Little time (<10 min/individual) was spent in contact with the transducer cage in Section 3.

Figure 7. Manatee interaction with the transducer cage, showing manipulation of the cage and its supports.

Table III. Sequence of trials conducted with 10 kHz transducer.

Date	Section	Time	Minutes Exposure	Stimulus	Level (RMS SPL)
3/13/03	3	–	None	None	–
3/18/03	3	9:03:10	13.2	10kHz 500 ms	130
	3	9:16:23	14.7		140
	3	9:31:05	1.4		150
	3	9:32:28	3.3		150
	3	9:35:43	9.3		150
3/19/03	3	8:44:00	16.3	10kHz 500 ms	140
	3	9:00:20	16.1		150
	3	9:16:23	14.7		160
	3	9:31:05	1.4		150
	3	9:32:28	3.3		160
	3	9:35:43	9.6		170
3/20/03	3	9:04:50	8.2	10kHz 500 ms	140
	3	9:13:02	15.9		180
	1	9:28:58	2.8		140
	1	9:39:40	2.5		140
	1	9:42:08	0.8		140
	1	9:42:53	0.1		180

Table IV. Observation time in manatee hours for each exposure condition.

Exposure Condition	Observation Time (Manatee-Hrs)
pre	459.92
10 kHz, off	1653.77
sonar	431.15
130 dB	150.90
140 dB	573.75
150 dB	271.30
160 dB	134.57
170 dB	83.17
180 dB	168.73
post	154.68
Total	3927.25

Notes: Exposure conditions - pre=period before transducer cage is mounted; 10 kHz, off = transducer cage mounted, but 10 kHz transducer not active; sonar = 171 kHz sonar mounted and active; 130-dB = 10 kHz transducer active and set to project pings at 130 - 180 dB; post = period after transducer cage removed.

At no time during the sequence of exposures to pings on 3/18 did the manatees react overtly to onset or changes in the sounds. At the end of the morning, they had touched both objects for similar proportions of the trial period.

During the trials on 3/19, manatees approached the toy as soon as it was placed in Section 1. One individual, Lil' Joe, approached the transducer cage and manipulated it while the transducer was pinging. Four of the manatees were observed engaging in social and sexual behaviors in Section 3 (near the transducer) during the series of trials. There was also a lot of social activity in Section 1 (**Figure 8**) as well. This was the first day that persistent social contact was observed, but the behavior was initiated and halted slowly and could not be associated with any given exposure level.

During the final set of trials on 3/20, the transducer cage was deployed with netting to prevent the manatees from pushing their pectorals and oral disks between the cage and the upright. The

Figure 8. Example of a bout of social behavior occurring in Section 1 in the 160-dB exposure condition during a trial on 3/19. The toy lies directly underneath them.

netting was composed of twine treated with plastic coating and the manatees apparently were attracted to the texture. While this netting was in the water, the manatees chewed at it and pulled on net and ropes. Animal Care staff had to push the manatees away to get the netting out of the water when they decided to remove it 15 minutes later. Once nthe etting was removed, manatees were less interested in the cage. When the pings were increased to the 180-dB exposure condition, some of the manatees swam slowly to Section 1. Webster, Slip, and Lil' Joe made the transition from Section 3 to Section 1 from 0910-0913, while Vail remained in Sections 3 and 2, and Eddie moved among all three sections. The transducer was moved to Section 1 at 0928 hrs and restarted with the 140-dB exposure. The manatees did not react by swimming back into Section 3. The 180-dB exposure condition was tested again briefly at the end of the morning, but husbandry constraints prevented the completion of this trial. The manatees did not respond to the increase in any obvious way. The initial 40-dB jump from the 140-dB exposure to 180-dB exposure was the only stimulus during the three days of trials that produced an avoidance response that could be detected by the observers on site.

Using the cumulative data from all three days of trials, the relationship between exposure condition and pool usage was examined. **Table V** shows the percentage of time spent in each section by exposure condition. No trend in usage with level was observed (**Figure 9**). **Table VI** shows use of the water column by exposure condition. **Figure 10** shows the trend in these data. There appeared to be an increase in usage of the upper half of the water column at levels in excess of 150 dB re 1uPa. However, the trend was not uniform – manatees spent more time in

Table V. Manatee usage of the test pool by exposure condition.

Exposure Condition	Section 1 - Toy (Manatee-Hrs)	%	Section 2 (Manatee-Hrs)	%	Section 3 – Sonar Cage (Manatee-Hrs)	%
pre	217.47	47%	132.17	29%	110.28	24%
10 kHz, Off	639.27	39%	591.53	36%	422.97	26%
sonar	247.68	57%	43.55	10%	139.92	32%
130 dB	56.48	37%	46.68	31%	47.73	32%
140 dB	267.17	47%	167.78	29%	138.80	24%
150 dB	86.55	32%	92.23	34%	92.52	34%
160-170 dB	93.82	43%	70.28	32%	53.63	25%
180 dB	80.38	48%	44.30	26%	44.05	26%
post	59.53	38%	47.38	31%	47.77	31%

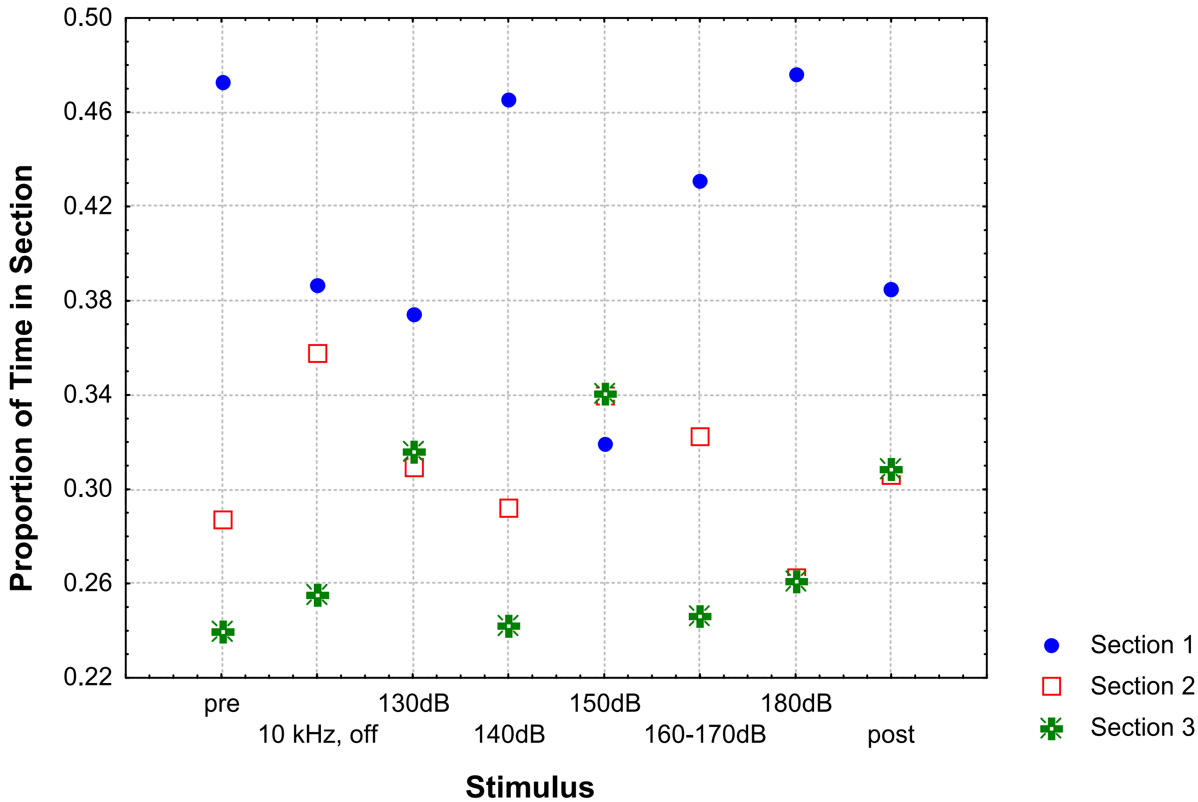

Figure 9. Graph showing proportion of time spent by manatees in each pool section by exposure condition.

Table VI. Manatee usage of the water column (bottom *vs.* top) by exposure condition.

Exposure Condition	Bottom (Manatee-Hrs)	Pct	Top (Manatee-Hrs)	Pct
pre	155.68	34%	304.2333	66%
10 kHz, Off	664.18	40%	989.5833	60%
sonar	135.32	31%	295.8333	69%
130 dB	77.60	51%	73.3	49%
140 dB	242.40	42%	331.35	58%
150 dB	175.15	65%	96.15	35%
160 dB	34.85	26%	99.71667	74%
170 dB	18.20	22%	64.96667	78%
180 dB	50.40	30%	118.3333	70%
post	51.73	33%	102.95	67%

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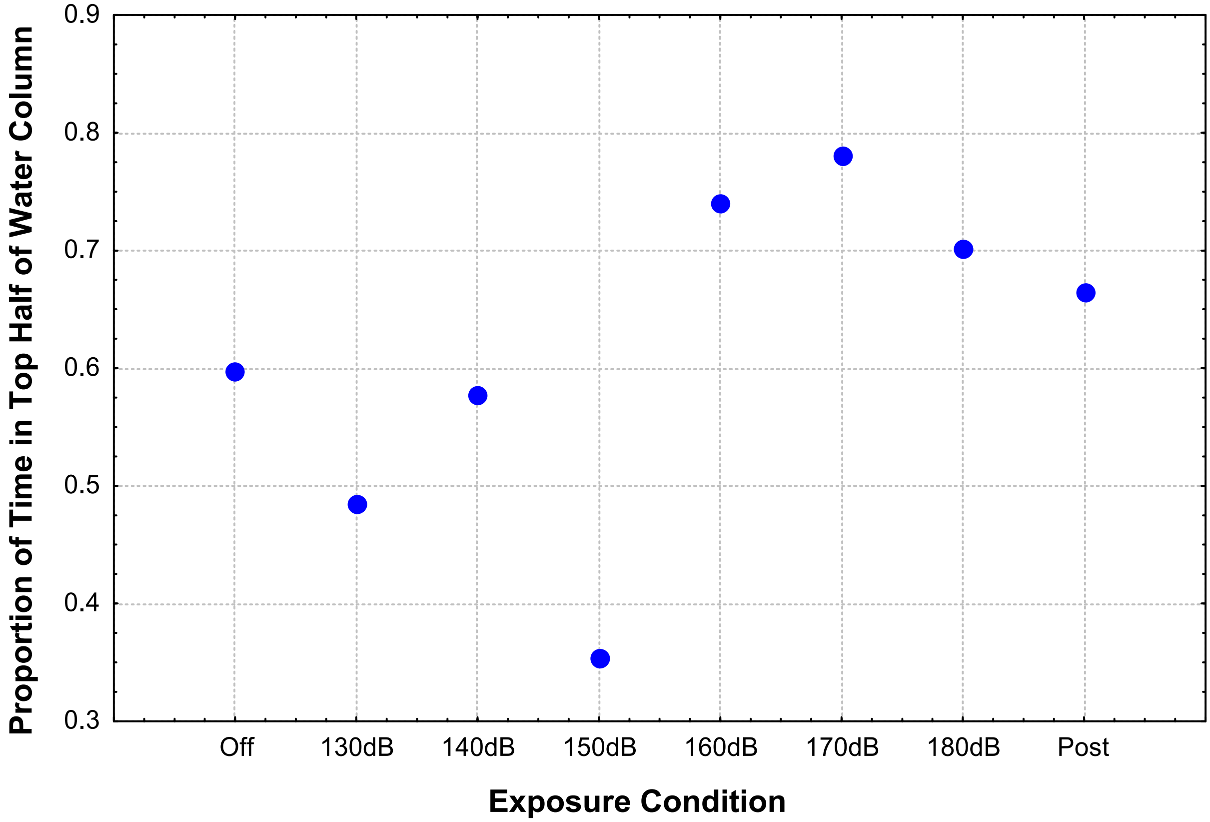

Figure 10. Graph showing proportion of time spent by manatees in top of pool by exposure condition.

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Table VII. Manatee swimming behavior by exposure condition.

pre	262	235.28	51%	92	113.13	25%	93	110.35	24%
10 kHz, Off	885	1008.03	61%	74	173.02	10%	534	470.87	28%
sonar	372	254.53	59%	55	38.77	9%	193	136.30	32%
130 dB	58	104.87	69%	9	18.25	12%	40	27.78	18%
140 dB	283	413.88	72%	31	54.93	10%	102	104.93	18%
150 dB	184	202.38	75%	22	31.93	12%	34	36.98	14%
160 dB	52	46.93	35%	9	13.65	10%	38	73.25	54%
170 dB	48	52.98	64%	10	13.67	16%	8	16.52	20%
180 dB	94	115.77	69%	1	0.35	0%	41	52.62	31%
post	81	96.17	62%	1	0.58	0%	42	57.93	37%

the top half of the water column when the transducer was off than in the 150-dB exposure condition, for example. The relationship between condition and depth was not significant ($p > 0.10$).

Behaviors that were potentially indicative of distress were also examined. Fast swimming, a possible sign of distress, was observed on only three occasions, once when the transducer was in the water, but off (transducer only), once during a post-trial period, and once when the 171 kHz transducers were active. It was never observed when the 10 kHz transducer was active.

Startle responses were observed eight times – two during the period before the transducer cage was introduced, one during the transducer only condition, two when the 171 kHz sonar was active, two during exposure to the 140-dB condition, and one during exposure to the 180-dB condition. In most cases, the cause of the startle response was difficult to ascertain. One startle response occurred during the 140-dB exposure condition, 3 min after the onset of pings. It was attributed to contact with a fish. The other two occurring during exposures were observed more than 5 min after onset.

Bubbling was observed four times in the transducer only condition, eight times in the sonar condition, and twice during exposure to the 10 kHz stimulus (140-dB and 150-dB conditions). The behavior was associated with cage manipulation and may have been a low-intensity aggressive gesture used when a manatee wanted access to the cage. Aggression (threats with the oral disk and paddle) occurred three times, once in the transducer only condition, and once each during trials in the 140-dB and 170-dB exposure conditions. Rates of these behaviors were too low to show significant trends with level.

No obvious changes in swimming behavior were observed with exposure condition (**Table VII**). Percent time spent swimming did not show a trend (lowest in the 160-dB condition, highest in the 150-dB condition). Swimming with rolling, a stereotypical behavior that could potentially have indicated anxiety, was less frequent when the transducer cage was present, in proportion to the time spent manipulating the objects. Swimming with rolling did not show a trend with exposure level.

Four common behavioral events were also examined, socializing and sexual interactions, touching the transducer cage, and touching the toy (**Table VIII**). A trend in percent time spent socializing and the rate of socializing bouts was observed. Bouts were longer as level increased (**Figure 11**). This trend was significant (Pearson Product Moment Correlation, $R = 0.82$, $t(6) = 3.59$, $p = 0.0114$). No trends in the other variables were observed ($p > 0.10$). The change in time spent socializing was apparent to observers on site.

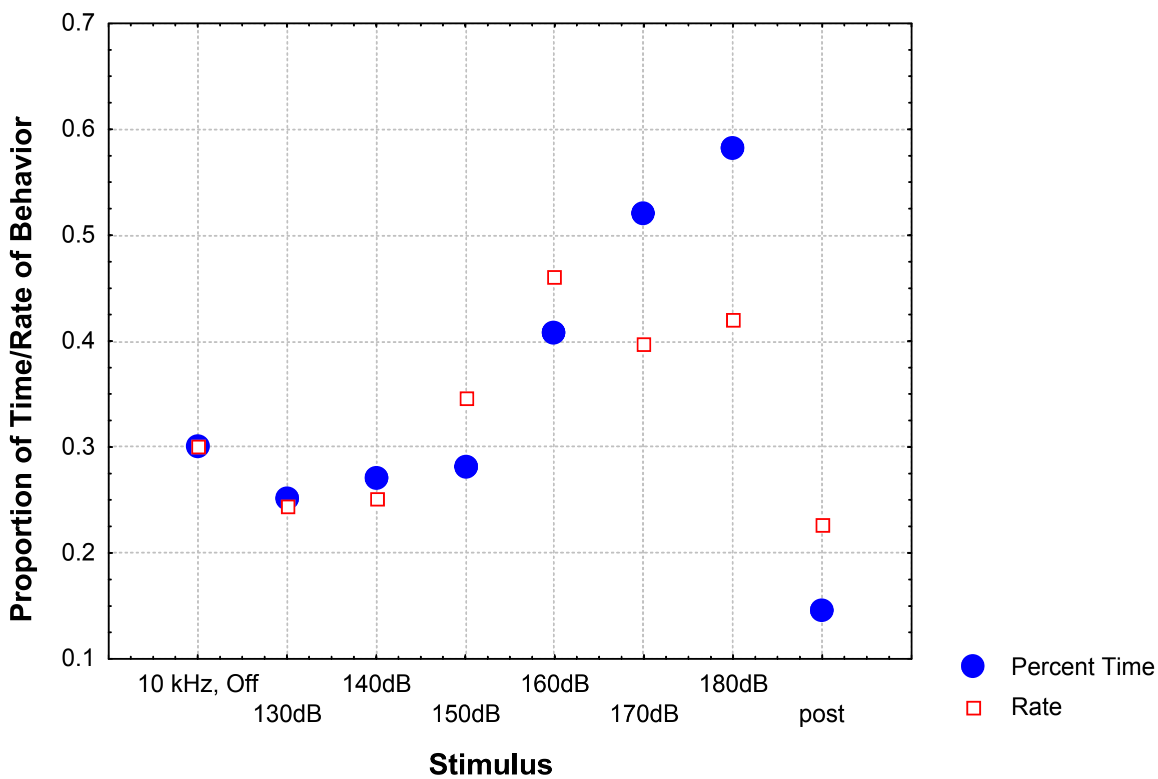

Figure 11. Graph showing proportion of time spent by manatees in social behaviors and the rate of bouts. This was the only trend in behavior that was significantly related to exposure level.

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Exposure Condition	Social			Touch Cage			TouchToy			Sexual		
	Bouts	Prop.	Rate	Bouts	Prop.	Rate	Bouts	Prop.	Rate	Bouts	Prop.	Rate
pre	127	0.21	0.28	-			16	0.017	0.035	17	0.033	0.037
10 kHz, off	498	0.30	0.30	251	0.10	0.152	89	0.027	0.054	9	0.004	0.005
sonar	208	0.30	0.48	52	0.08	0.121	53	0.079	0.123	10	0.014	0.023
130 dB	37	0.25	0.25	1	0.26	0.007	17	0.082	0.113	0	0.000	0.000
140 dB	144	0.27	0.25	35	0.04	0.061	27	0.019	0.047	4	0.046	0.007
150 dB	94	0.28	0.35	14	0.03	0.052	11	0.018	0.041	3	0.006	0.011
160 dB	62	0.41	0.46	1	0.18	0.007	6	0.039	0.045	1	0.003	0.007
170 dB	33	0.52	0.40	4	0.03	0.048	0	0.000	0.000	1	0.007	0.012
180 dB	71	0.58	0.42	0	0.00	0.000	22	0.079	0.130	1	0.002	0.006
post	35	0.15	0.23	1	0.11	0.006	2	0.010	0.013	2	0.006	0.013

Table VIII. Proportion of time spent in social behaviors, touching objects, and sexual behaviors by exposure condition. Rates of these behaviors are indicated as well.

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Sonar reflectivity measurements

Behavioral responses. Manatees never exhibited avoidance or behaviors indicative of distress in response to the 171 kHz reflectivity measurements. They manipulated the transducer cage in the same manner as during the transducer only condition (**Figure 12**). They spent more trial time in Section 1 during the reflectivity measurements than during any other condition (57% of time *vs*. 39% during the transducer only condition), but this was the result of spending less time in Section 2 rather than less time in Section 3, where the transducer cage was located. They spent slightly more time (32%) during reflectivity measurements in Section 3 as opposed to the transducer only condition (26%); however, the difference was not significant ($p > 0.10$).

During the reflectivity measurements, proportion of time in the top half of the water column and proportion of time spent swimming (**Table VI, VII**) differed little with respect to the pre, transducer only, and post exposure periods. The manatees contacted the transducer cage almost as much during the reflectivity measurements as during the transducer cage only trials (**Table VIII**) and at a much greater rate than any of the experiments with the actively pinging 10 kHz transducer (0.12/min as opposed to 0.06/min at the most). Contacts with the toy in Section 1 were as high as during the 130-dB and 180-dB exposure conditions. The proportion of time spent socializing was comparable to that in the transducer only condition (**Table VIII**), but the rate of social contacts was as high as the during 10 kHz trials. Possible explanations for the differences during reflectivity measurements will be presented in the 'Discussion' section.

Reflectivity measurements. The results of the sonar reflectivity experiments are summarized in the histogram of inferred target strengths (**Figure 13**). In all cases, the animal reflected less energy than the sphere, in some cases by a factor of 10 dB, an intensity an order of magnitude lower than the -29 dB test sphere. The fact that a 400-700 kg manatee could reflect less energy than a 5 cm sphere was surprising. At first, these extremely low numbers were considered suspect. However, the data were reviewed with other sonar experts (D.V. Holliday, pers. comm; W.W. Au, pers comm.) and bioacousticians, who concluded that these values were defensible and that the approach taken was valid. Therefore, the data collected during this study show that the reflectivity of the manatee is somewhat low, in the -49 dB to -40 dB range.

DISCUSSION

Exposure to 10 kHz sonar. It was clear that the manatees detected the 10 kHz pings easily. They approached the transducer cage when the signal was initiated each day. More subtle behavioral changes were also observed (slow swimming to the opposite end of the pool, a change in social behavior). However, even at the highest ping levels, none of these behaviors were suggestive of intense avoidance responses or distress. Such behaviors have been observed in response to other types of stimuli, particularly physical contact (Bowles, pers. obs.; also reported by Animal Care Staff). Therefore, it seems likely that manatees do not have a strong

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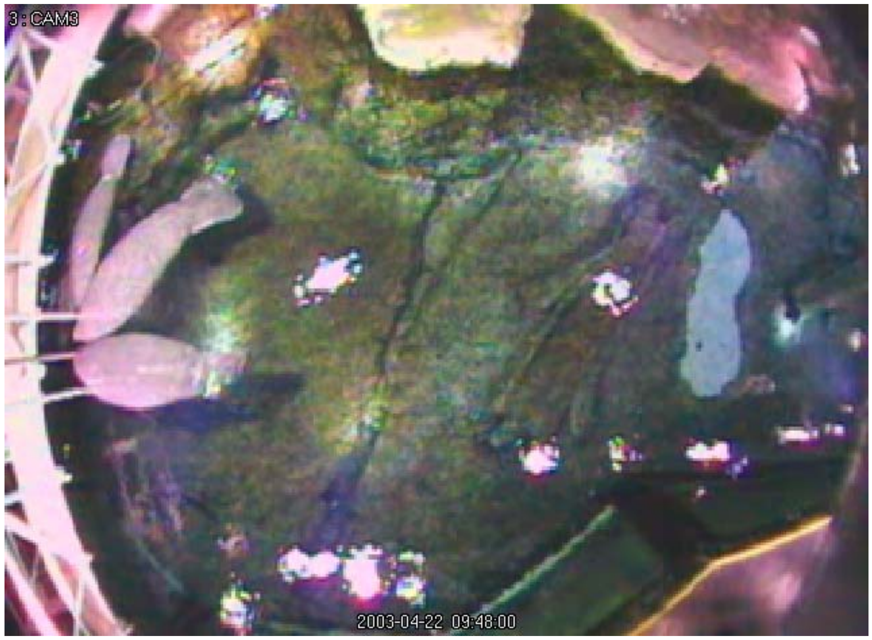

Figure 12. Manatees manipulating the transducer cage during a sonar reflectivity trial on 4/22/04. The transducers had been active for nearly an hour at the time this image was collected.

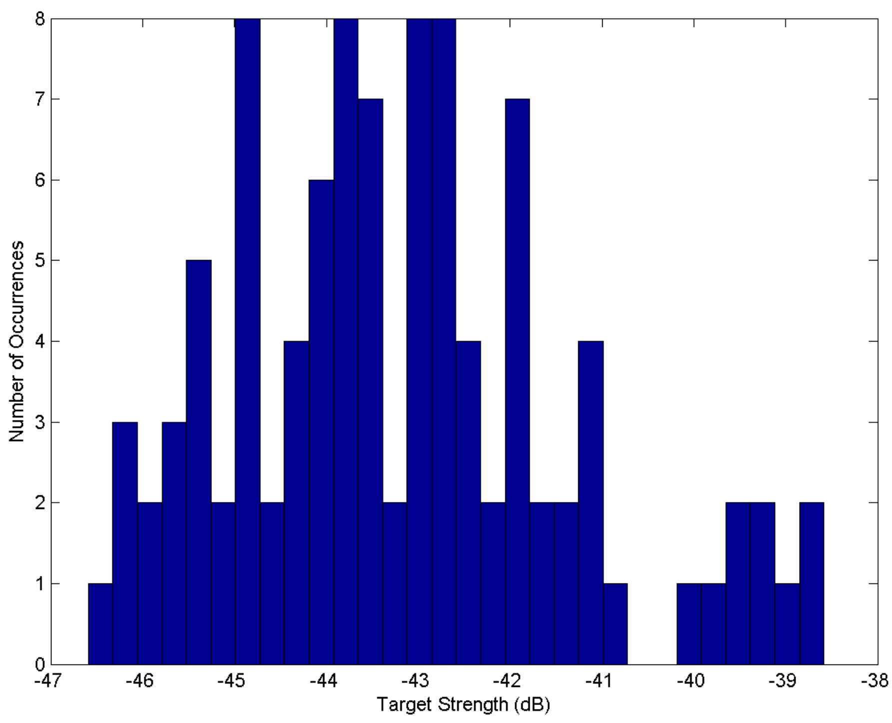

Figure13. Frequency distribution of the 100 reflectivity measurement.

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acoustic startle responses and aggressive gestures of the type observed during pinger trials with pinnipeds and small cetaceans (Anderson et al. 1998). These results are consistent with a series of earlier trials with a 10-kHz Netcom 1000 pinger (130 dB re 1 uPa)(Bowles *et al*. 2001b) presented to manatees for periods of 30 min. The manatees' tendency to approach the transducer when it first began to emit pings, absence of startles, and failure to demonstrate a reliable avoidance response suggest that intense tone pips cannot be used as warning signals for manatees in and of themselves. Some other negative stimulus would have to be paired with pings to produce reliable avoidance.

The manatees did exhibit slow responses to the 10 kHz pings. In one case, they swam from Section 3 to Section 1 three minutes after a 40-dB increase in level. Across all the trials, a significant relationship between level and time spent socializing was found. It is tempting to assume that the increase in time spent socializing was evidence of congregation, a common response to disturbance among marine mammals (Richardson *et al*. 1995). However, an alternate explanation should be considered. The step-up design of the trials was selected to because the threshold of tolerance of manatees was not known initially - it ensured that manatees were never exposed to intolerable levels abruptly. However, this approach produced an unavoidable bias in the series of experiments. As level increased, the manatees became increasingly familiar with the trial procedures. Therefore, it is possible that habituation could have caused a change in motivation to socialize over time. Because it is clear that manatees to not exhibit strong evidence of distress, randomized trials should be planned to eliminate the correlation between level and time, to determine whether a reliable dose-response relationship with level could be found.

Sonar reflectivity experiments: It is interesting to speculate why the sonar reflectivity values measured were so small. Two possibilities exist: (1) The animals are acting like a mirror and most of the sound was reflected in other directions. Consistent with this theory is the observation that small movements of the manatees resulted in large changes in the observed reflections. It is also possible that (2) the manatees were actually absorbing sound because their bodies have almost the same acoustic impedence as the water. The second possibility is attractive because it explains the differences in estimated target strength of manatees as opposed to fish and bottlenose dolphins (Bertrand and Masse 1999, Au 1993). Kipps *et al.* (2002) have shown that manatee skin and blubber differ in density from small cetaceans of similar size. Since reflected energy was only measured in the backscatter direction, the two possibilities could not be differentiated.

Previous measurements were also conducted using pings at lower frequencies. In particular, Au (1993) found that target strengths were greatest for the bottlenose dolphin at frequencies in the range from 10 - 80 kHz. Future trials will be planned to determine whether better returns can be obtained from manatees at lower frequencies and also to determine whether a disturbance threshold can be found at frequencies that provide good returns.

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Appendix A: Manatee Ethogram

Definitions of Behavior Events and States and Location Variables

Behaviors are divided into events and states. Events are very short, and are simply counted. States persist for a period of time; both counts and total numbers of bouts are recorded.

BEHAVIORAL EVENTS:

Approach Object	Manatee moves toward object (sonar cage or toy), from half a body length to one pectoral flipper length
Contact Object	Manatee comes into physical contact with the object (sonar cage or toy)
Startle	Body jerk with no directional movement; cause of startle specified when possible
Fast Swim	Quick burst of swimming in any direction
Bubble	Blowing bubbles from snout or mouth
Aggressive	An aggressive gesture oriented on an object or other manatee, typically ramming or rapid flip of paddle
Social	Physical contact with another manatee for longer than two seconds

POOL REGION (see Figure 1)

1 West end of the pool; sonar cage location during most experiments
2 Center of pool
3 East end of the pool; toy location during most experiments

D. Manatee in the bottom (deep) half of the water column
S. Manatee in the top (shallow) half of the water column

ACTIVITY STATES

Swim_Roll	Manatee swimming in any direction, rolling repeatedly
Swim_No Roll	Manatee swimming in any direction, not rolling.
No Swim_Roll	Manatee stationary, rotating in the water
No Swim_No Roll	Manatee stationary, not rotating
Feeding	Manatee mouthing or eating food at the surface of the pool

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