Measurement of the acoustic reflectivity of sirenia (Florida manatees) at 171 kHz

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The Florida manatee (*Trichechus manatus latirostris*) is an endangered sirenian. At present, its adult population (~2200) seems stable, but tenuous. Manatee-boat collisions are a significant proportion (~25%) of mortalities. Here, the potential use of active sonar for detecting manatees by quantifying sonic reflectivity is explored. In order to estimate reflectivity two methods were used. One method measured live reflections from captive animals using a carefully calibrated acoustic and co-registered optical system. The other method consisted of the analysis of animal tissue in order to obtain estimates of the sound speed and density and to predict reflectivity. The impedance measurement predicts that for a lateral view, the tissue reflectivity is close to 0.13, with a critical grazing angle of 28°. Data measured from live animals indicate that substantial reflections can be recorded, however in many instances observed "empirical target strengths" were less than an experimentally dependent −48-dB threshold. Conclusions favor the hypothesis that the animals reflect substantial amounts of sound; however, the reflections can often be specular, and therefore impractical for observation by a manatee detection sonar operating at 171 kHz. © *2007 Acoustical Society of America.* [DOI: 10.1121/1.2384845]

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I. INTRODUCTION

The Florida manatee (*Trichechus manatus latirostris*) is an endangered sirenian inhabiting the shallow coastal waters of Florida (USA). At present, its adult population (~2200) appears to be stable or increasing (Craig and Reynolds, 2004; Langtimm *et al.*, 2004; Florida Manatee Biological Review Panel, 2005), but natality and mortality have been nearly equal in recent years, suggesting that the population has limited potential for growth. Human-caused mortalities account for a significant proportion of the mortalities, approximately 25%. Collisions with watercraft are the major cause [on average 24% of losses over the last five years; in 2005 80 manatees died in collisions (Florida Fish and Wildlife Conservation Commission, unpublished; Marine Mammal Pathobiology Lab, 2005)]. Furthermore, this is the only cause of mortalities that can be managed directly. Therefore, Florida management agencies are actively supporting research to find ways of reducing collisions, particularly if they can be used to reduce mortalities while maintaining recreational opportunities for millions of registered boaters. Sonar techniques certainly have this potential.

One strategy for reducing manatee-boat collisions consists of alerting the boater to the presence of the animals. Given suitable time to respond, the boater can take action to minimize the chance of collision. Active sonar systems have the potential to fulfill the role of detecting animals at suitable ranges provided they can function in the manatee habitat and the animals are sufficiently reflective.

Although the intent of the article is not to summarize in detail the various strategies that might be used to detect the presence of manatees, we do remark that various researchers have been concerned with this problem over the years. Work (Gerstein, 2002) suggested that the animals cannot hear an oncoming craft because of the Lloyd's mirror effect. Certainly this makes the animal's job of evading boats more difficult. In order to ameliorate the situation, it has been suggested that motor craft in areas frequented by manatees carry an acoustic transmitter so that the animals will be alerted to the presence of boats. To our knowledge, the success of this strategy has not been tested under field conditions. In the laboratory, manatees respond to audible tone pips by approaching and manipulating sound sources (Bowles *et al.*, 2001; Bowles, 2002). They have also been shown to respond in unpredictable and potentially inappropriate ways to boat noise (Nowacek *et al.*, 2004). An alternative that has been tested is passive detection using vocalizations. Manatees produce short chirps in the range from 500 Hz to 6 kHz, with most energy at 2–3 kHz (Schevill and Watkins, 1965; Gerstein *et al.*, 1999; Niezrecki *et al.*, 2003). However, estimated source level for the vocalizations is very low (maximum 110 dB *re*:1 μPa @ 1 m) and the manatees only vocalize intermittently. In addition, the sounds are sometimes difficult

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to distinguish from other short transients in the manatee habitat, especially at low signal-to-noise ratios. Therefore, the method is likely to be most effective when used concurrently with other techniques.

Although the active acoustic detection of manatees theoretically is an option, there has been little work in estimating sonar reflectivity of large marine animals. Probably the closest underwater acoustic models of the manatee that have been subjects of target strength measurements are cetaceans. Au (1996) measured target strengths of bottlenose dolphins of −11 to −23 dB as a function of frequency between 23 and 79 kHz. Measurements showed a strong dependence on dolphin orientation. However, the available evidence indicates that dolphin blubber and skin differ from those of the manatee (Kipps *et al.*, 2002), suggesting that the sonic properties of manatees are quite different as well. Such differences may explain why previous attempts to detect manatees using sonar have not been particularly successful (e.g., Dickerson *et al.*, 1996).

With respect to larger animals, Miller and Potter (2001) formulated a three-layer model in conjunction with density and sound speed estimates of right whale skin and blubber in order to predict target strengths. These were then compared with field data and good agreement was found. Based on skin measurements (density, sound speed) of 1700 m/s and 1200 kg/m^3 and blubber (density, sound speed) estimates of 1600 m/s and 900 kg/m^3, they predicted target strengths at 86 kHz to be between 0 and −5 dB depending on blubber thickness (0–30 cm). Measured target strengths of two adult right whales were consistent with these estimates.

Based on lack of data on manatee reflectivity and the increasing interest in estimating the possible role that active sonar might play in reducing animal-boat collisions, a program to measure animal sonic reflectivity was undertaken. In order to measure the sonic reflectivity of the Florida manatee, two measurement techniques were employed. The first consisted of measuring reflections from captive animals in an enclosed pool using a calibrated sonar system. Another method used frozen and subsequently thawed animal tissues to measure sound speed and density, from which acoustic impedance could be calculated. These measurements resulted in an estimate of reflectivity as a function of angle, including the critical angle at which all sound was reflected.

Since the thick manatee "skin" is mostly composed of densely woven collagen (Kipps *et al.*, 2002; Sokolov, 1982), the acoustic properties of this material are relevant. Collagen is the most abundant protein in mammals (White *et al.*, 1968), contributing 17% of the total body mass and 70% of the negative buoyant force (Sokolov, 1982). Density in its native state can vary from 1160 to 1330 kg/m^3 (Hulmes *et al.*, 1977; Dweltz, 1962). Such dense protein exhibits remarkably high ultrasonic attenuation, absorption, and velocity in tissues. Goss and Dunn (1980) studied the ultrasonic propagation properties of collagen and estimated a sound speed of 2094 m/s in a sample with a collagen concentration of 80%, at 20 °C at 8.97 MHz. More directly applicable to this study, Kipps *et al.* (2002) measured the skin density from 27 male and female manatee carcasses. The average observed value was 1121 kg/m^3.

Goss and Dunn (1980) established an acoustic absorption coefficient per unit concentration in collagen suspension at 20 °C as a function of frequency as $\alpha_C = 114 f^{-0.53}$, where f is the frequency in MHz and α_C is the absorption coefficient per unit concentration. Attenuation can then be calculated via the expression $\Delta\alpha = \alpha_C f^2 C_S$, where C_S is concentration, in dB as $\Delta\alpha_{dB} = \log_{10}(e)\Delta\alpha$. Agemura *et al.* (1990) obtained attenuation results of 80 dB/mm at 100 MHz from articular cartilage (composed of mostly collagen) of young steers. This result is slightly lower than that measured by Goss at 86 dB/mm. Extrapolating these results using Goss' formula yields an expected value of 2.3 dB/mm at 10 MHz and 0.6 dB/mm at our working frequency of 171 kHz.

II. METHODS

A. Sound speed and density measurements

Owing to the difficulty of working with live animals, both the density and sound speed measurements were obtained from a post-mortem subject. Samples were collected from an adult male that collided with a boat on 22 April 2004. Shortly after the collision, the manatee was euthanized, and samples were collected within 1 h of death and then frozen. Three 8×8 cm^2 samples were extracted from the dorsal, lateral, and ventral aspects of the manatee at the umbilicus that included skin and the full depth of blubber. Before the tests were performed, the samples were thawed, divided into smaller pieces, and then refrozen for storage.

1. Dissection

Figure 1 shows the dorsal, lateral, and ventral samples. All three skin samples were composed of a thin epidermis (2 mm) over a thick dermis, which was attached to blubber and muscle. The three samples had different skin thicknesses, 1 cm on the ventral, 1.7 cm on the dorsal, and 2.4 cm on the lateral aspect. The dorsal sample had ~1 cm of blubber followed by muscle, the lateral sample had a thicker layer of blubber (~2 cm) and then muscle. The ventral sample had skin attached to a ~1-cm layer of blubber followed by muscle (~2 cm), then more blubber (~1 cm) and another muscle layer.

2. Sound speed and attenuation

Sound speed was measured using a Krautkramer Branson USD10 Ultrasonic Digital Flaw Detector with two Krautkramer Branson transducers (Alpha series, 10 MHz, 0.25 mm) mounted onto a Mitutoyo digital caliper (Model CD-8"CS) (Fig. 2). The Krautkramer equipment was used to measure the delay time of the transmitted pulse from the top to bottom transducer. Prior to use, the instrument was calibrated by measuring the travel time for a 10-MHz pulse to propagate through a manufacturer-supplied copper strip (with known sound speed) and also distilled water at 19.5 °C whose sound speed is known to be 1490 m/s. Calipers were used to measure the sample thickness before the sound speed measurement. The sound speed was then computed as the ratio of the thickness to the time interval between transmit and receive pulse. Attenuation was computed as

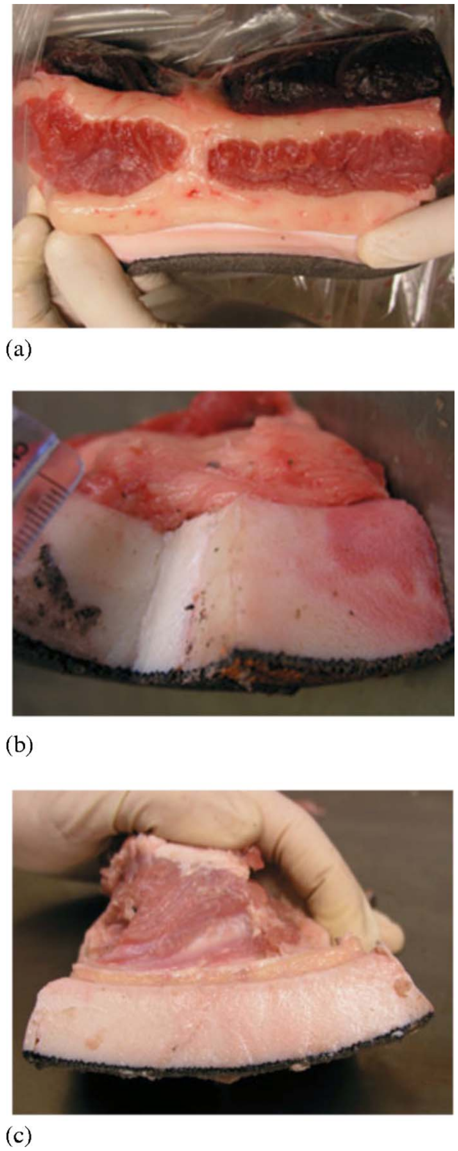

FIG. 1. (Color online) (a) Ventral sample. (b) Lateral sample. (c) Dorsal sample (figure online).

$10 \log_{10}(I_{rec}/I_{inc})/\Delta x$, where I_{rec} is the intensity of the received waveform, I_{inc} is the intensity of the transmitted waveform, and Δx is the sample thickness. Results (in dB/mm) were observed at 10 MHz.

Since the sound speed and attenuation measurements were performed at 10 MHz (high frequencies are needed to keep samples down to a workable size), some extrapolation to the frequency employed at 171 kHz was necessary. Assuming that the medium is nondispersive implies that the sound speed will be the same at 171 kHz as it is at 10 MHz. Unfortunately, the attenuation results cannot be treated in a similar manner because absorption and scattering change significantly as a function of frequency.

FIG. 2. (Color online) The experimental configuration used for the sound speed measurements (figure online).

3. Density

In order to compute sample density, samples were submerged in a graduated cylinder in distilled water and the resultant increase in volume displacement and sample weight was measured using a Sartorius Handy H51 scale (0.0001 g accuracy). Density was calculated as mass/volume.

4. Acoustic impedance

Acoustic impedance determines how much sound is transmitted and reflected at any given boundary. Using the familiar Fresnel law of reflection, the reflection coefficient at the manatee-water interface can be calculated as

$$R_{W-M} = \frac{\rho_M c_M - \rho_W c_W}{\rho_M c_M + \rho_W c_W}, \tag{1}$$

where ρ_M and c_M are the density and the sound speed of the manatee skin and ρ_W and c_W are the density and the sound velocity in the fresh water pool. Reflectance (R) as a function of incidence angle α can then be estimated as

$$R = \frac{\cos \alpha - b\sqrt{\sin^2 \alpha - \sin^2 \alpha_C}}{\cos \alpha + b\sqrt{\sin^2 \alpha - \sin^2 \alpha_C}}, \tag{2}$$

where $b = \rho_1/\rho_2$ and the critical grazing angle, where grazing angle is defined as the angle between a plane parallel to the surface and an incident ray $\alpha_C = \cos^{-1}(c_1/c_2)$.

B. Measurement of the acoustic reflectivity of live manatees

An estimate of live manatee acoustic reflectivity will be described in this section. Working at the Manatee Rescue facility at SeaWorld San Diego, a series of experiments was performed in order to estimate animal target strength. The measurements were complicated by the fact that they were necessarily performed in the near field of the acoustic system. In addition, because of the large size of the animal, the sonar system was in the near field of the energy reflected from the manatee. As a candidate choice of frequency, based mainly upon the availability of hardware, a frequency of 171 kHz was used. This frequency was well above the upper limit of hearing of the manatee (Gerstein *et al.*, 1999) and bottlenose dolphin (Johnson, 1967), the two marine mammal species that could be encountered in areas where an avoidance sonar might be deployed. Additional complications that arose in the course of performing the experiments were due to the high level of ambient electrical noise. In addition, significant reverberation due to the geometry of the pool made it difficult to interpret data from ranges greater than

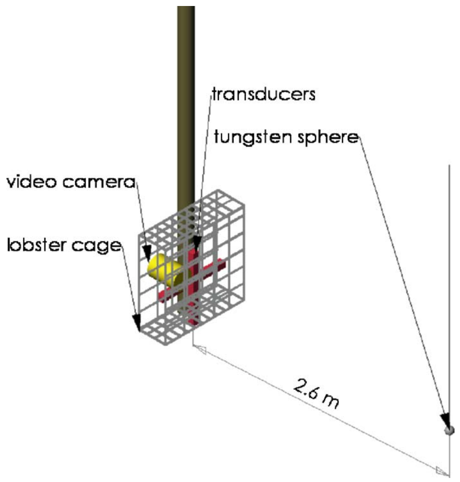

FIG. 3. (Color online) A diagram of the calibration setup consisting of (two) side scan transducers, a video camera, and a tungsten carbide sphere mounted inside of a cage.

4–5 m. Coupled with the seemingly low reflectivity of the manatees, the use of simple techniques for measuring target strengths was precluded.

1. Calibration of the sonar equipment

The permit for the experiments allowed a maximum source level of 180 dB $re:1\ \mu$Pa @ 1 m. To calibrate source level, an E-8 Navy calibrated transducer was used as a hydrophone. The hydrophone was positioned at a known distance from the source and the output of the transducer was determined for a given input voltage amplitude using the sonar equation (Urick, 1967). Input voltages were adjusted so that the source level was always below 180 dB.

In order to measure animal reflectivity, two transducers of size 15 mm by 498 mm were employed. The approximate beam pattern in the far field of the transducers at 171 kHz (center frequency) was 20° by 1° as measured in the Transducer Evaluation Center (TRANSDEC), Naval Ocean Systems Center, San Diego. The sonars were mounted at right angles to each other as shown in Fig. 3, with one used in transmit mode while the other was used to receive. The resultant composite beam did not spread very much as the far field pattern is approximately $1° \times 1°$. This helped to reject the reverberation from the pools walls and air-water interface, providing a practical solution to the reverberation problem at modest ranges (1–4 m).

In fisheries acoustics, a standard technique for calibrating a sonar system involves the use of calibrated spheres (Vagle *et al.*, 1996). In a typical application, a sphere of known reflectivity and size and therefore measurable target strength is positioned at various three-dimensional locations in the field of view of the sonar transducer(s). The system response (output voltage of the system from the echo relative to input voltage) is then measured for each location. These values are then used to calibrate the system by noting the relationship between output levels as a function of target position. Given a measurement of target position, input, and output level, the target strength from a target at a measured position can then be estimated via extrapolation of these results when combined with an understanding of the three-dimensional energy density incident on targets with spreading loss via use of the sonar equation (Urick, 1967).

The procedure for the manatee experiments was based on this protocol. However, the exact reflectivity of a manatee in the sonar's field of view was more difficult to judge because, even at the furthest range of 5 m, the animal was in the near field of the sonar. So, for example, given a transducer of dimensions 15 mm by 498 mm, and using the formula for the start of the far field as D^2/λ (Kino, 1987), the start of the far field for the larger dimension was estimated to be 35 m. Although smaller transducers could be used and, hence, decrease the distance to the far field, a larger incident sound field pattern would result, perhaps complicating the measurements even more. In consideration of this, it was decided to use our existing transducers.

Since the goal of the experiment was to explore the potential use of an active sonar system to detect acoustic reflections from manatees, it was decided that some quantitatively determined proxy of animal reflectivity would suffice. Although the results are not entirely general in that they cannot be expressed as being the true target strength of the animal, a quantity that is independent of the exact geometry of the measuring apparatus, our system was calibrated and the results can be communicated to other researchers using a protocol that can be readily duplicated.

The experiments proceeded by characterizing the reflectivity of the manatee at a known set of three-dimensional locations relative to a small, exactly calibrated, and precisely positioned target. Given a voltage from the test target, V_{target} (−39 dB), and the voltage output from the manatee, V_{manatee} (at the same position), the estimated, empirically observed, "relative target strength" was defined as

$$TS_{\text{rel}} = 20 \log_{10}\left(\frac{V_{\text{manatee}}}{V_{\text{target}}}\right) - 39. \qquad (3)$$

In order to judge both animal and test target position in three dimensions during the experiments 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 allowed judgment of the bearing angle, while the reflected acoustic pulse permitted an estimate of range. Hence, the three-dimensional position of the animal could be measured. Past experiences with combining optics and acoustics resulted in enhanced characterization of targets (Jaffe *et al.*, 1998) and their precise three-dimensional locations (Schell and Jaffe, 2004).

The video camera and sonar transducers were calibrated together by translating a 38-mm tungsten carbide sphere (Foote, 1990), of target strength [TS]=−39 dB @ 171 kHz, in the test tank. The sphere was translated in two dimensions at several ranges while both video images and sonar reflections were recorded. Thus, effective beam patterns of the sonar were recorded for this omni-directional reflector, as measured at approximately 100 points in the field of view of the system over several ranges (1, 2, and 2.6 m).

Results indicated that at the very shortest ranges, 1 and 2 m, the near-field sound pattern was quite complicated. However, at 2.6 m, the field became a more interpretable sound pattern. At this and greater ranges, a "system response" could be used to estimate animal reflectivity from the calibration measurements.

At the completion of the calibration, the voltage obtained via reflection from the sphere could be accurately predicted as a function of absolute three-dimensional position. In addition, the calibration curves from data collected with the sphere at 2.6 m were extrapolated to a slightly greater range (4 m) for use. 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 from a target positioned at 4 m, extrapolated from the 2.6 m data.

2. Measurement of "relative" target strengths

The sonar setup was mounted in a protected cage to ensure that the manatees could not harm themselves or the equipment. The signals were 1-ms frequency swept "chirps" from 150 to 190 kHz. Output levels were kept within a safe range for manatee hearing in compliance with a permit that allowed performance of the experiments. Pressure levels 1 m from the sonar transducers were smaller than 180 dB *re*:1 μPa. Data from approximately 120 reflectivity measurements were used in the following analysis.

The processing method consisted of applying a matched filter detector to the received signals that was exactly the same as the transmitted wave. The resultant signal was displayed in "real time" so that the observer could monitor the results of the experiments. As an added calibration check, the spherical test target was also deployed in the field of view of the coincident optical-acoustic system during the experiments. This added measure insured that the reported values were truly related to the calibrated target.

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. Based on analysis of the background noise level in the pool a value of −48 dB *re*:1 μPa was established. All reflections at least 10 dB over this threshold were considered to be potential returns from manatees. Upon detection of a sonar reflection that exceeded this value, the concurrent video data were inspected to see if manatees were present. Results indicated that a manatee was present in the field of view of the sonar system at the appropriate range in every case. Therefore, although the noise level in the pool was high, reflectivity from the manatees at ranges to 4 m were adequate to obtain unambiguous identification.

After acoustic detection, the video images were inspected to determine the section of the field of view of the sonar that the 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. The output voltage of the system was then used to compute the relative target strength via Eq. (3). This value constituted an estimate of target strength in dB. Taking the point inside the field of view with the largest V_{target} resulted in a conservative estimate of the animal's target strength. Other, less reflective areas would have yielded a higher ratio and therefore a larger inferred target strength for the manatee. However, the latter procedure was found to be numerically unstable in that the smaller values had more variability and were noisier. Moreover, the approach taken yielded an estimate of what might be expected from such a system in a practical sense.

III. RESULTS

A. Tissue measurements

In order to obtain an estimate of inherent variability in the tissue estimates of acoustic impedance the measurements were performed on many subsamples (connective tissue, blubber and muscle) that were extracted from ventral, dorsal, and lateral samples from approximately the midpoint of the body (at the umbilicus). Measurements were done at 21 °C (see Table I for results).

B. Acoustic reflectivity measurements

Figure 4 is a histogram of the observed relative target strengths for the more than 120 cases where the reflected signal was adequately above the noise level in the pool to be clearly detected. We note that in almost all cases, the reflected energy was substantially greater than that of the calibrated sphere. Although we know of no comparable values for other marine mammals at this frequency, the values seem reasonable especially when compared to the work of Au (1996) on bottlenose dolphins.

IV. DISCUSSION AND CONCLUSIONS

A. Tissue samples

Results for the connective tissue samples indicated an average sound velocity, density, and attenuation of 1708 m/s, 1149 kg/m^3, and 3.4 dB/mm (at 10 MHz), respectively. Table II contains a summary of the estimated reflection coefficients for the different regions. Reflection coefficient calculation under the Connective Tissue (CT) column is the reflection from the water-CT interface, under the Outer Blubber (OB) column is from the CT-OB interface, under the Outer Muscle (OM) column is from the OB-OM interface, under the IB column is from the OM-IB interface and, lastly, under the IM column is from the IB-IM interface.

To show the relationship of reflectivity to the angle between the incident sound wave and a plane parallel to the surface, a graph of reflectivity versus angle was then plotted using the data from the lateral umbilicus (1708 m/s and 1149 kg/m^3, from Table I) and the sound speed and density measurements in the manatee pool (1510 m/s and 1000 kg/m^3, respectively). Figure 5 shows the graph.

TABLE I. Sound velocity, attenuation, and density measurements of manatee tissue samples. CT=connective tissue, OB=outer blubber, OM=outer muscle, IB=inner blubber, IM=inner muscle, and n=number of samples.

Lateral	CT (n=7)	OB (n=7)	OM	IB	IM
Sound velocity (m/s)					
Mean	1707.82	1529.30	n/a	n/a	n/a
Standard deviation	5.75	8.34	n/a	n/a	n/a
10 MHz attenuation (db/mm)					
Mean	3.43	5.57	n/a	n/a	n/a
Standard deviation	0.20	1.66	n/a	n/a	n/a
Density (kg/m^3)					
Mean	1148.80	965.12	n/a	n/a	n/a
Standard deviation	70.53	63.78	n/a	n/a	n/a
Dorsal	(n=9)		(n=2)		
Sound velocity (m/s)					
Mean	1704.20	n/a	1601.77	n/a	n/a
Standard deviation	6.23	n/a	19.47	n/a	n/a
10 MHz attenuation (db/mm)					
Mean	4.18	n/a	3.39	n/a	n/a
Standard deviation	0.43	n/a	1.29	n/a	n/a
Density (kg/m^3)					
Mean	1113.60	n/a	1018.61	n/a	n/a
Standard deviation	40.58	n/a	2.94	n/a	n/a
Ventral	(n=6)	(n=6)	(n=6)	(n=6)	(n=6)
Sound velocity (m/s)					
Mean	1679.81	1525.42	1621.10	1519.01	1626.87
Standard deviation	13.16	17.58	10.05	21.91	10.65
10 MHz attenuation (db/mm)					
Mean	5.64	5.02	3.71	7.80	4.87
Standard deviation	0.88	0.64	0.81	1.48	1.06
Density (kg/m^3)					
Mean	1029.92	1064.42	1067.85	1023.21	1072.60
Standard deviation	63.78	106.66	42.64	108.53	82.01

B. Acoustic reflectivity measurements

As one aspect of this work, it is of interest to reconcile the "relative target strength" measurements with the reflectivity estimates in order to predict observed target strengths from the reflectivity data. To this end, an approximate target strength can be estimated as follows: Assuming the area subtended by the sonar at the target due to the composite beam pattern of $1° \times 1°$ is equal to A_{inc}, the power integrated over this area can be computed as $I_{\text{inc}}A_{\text{inc}}$, where I_{inc} is the intensity of the incident field. Next, the reflected power can be computed via multiplication by the reflectivity of the target ρ to yield $\rho I_{\text{inc}}A_{\text{inc}}$. The acoustic intensity measured at a 1-m range in the backscatter direction can them be computed by dividing this quantity by the area subtended by the backscattered hemisphere: 2π. Taking the logarithm of the ratio of this quantity to the incident acoustic intensity yields an estimate of target strength:

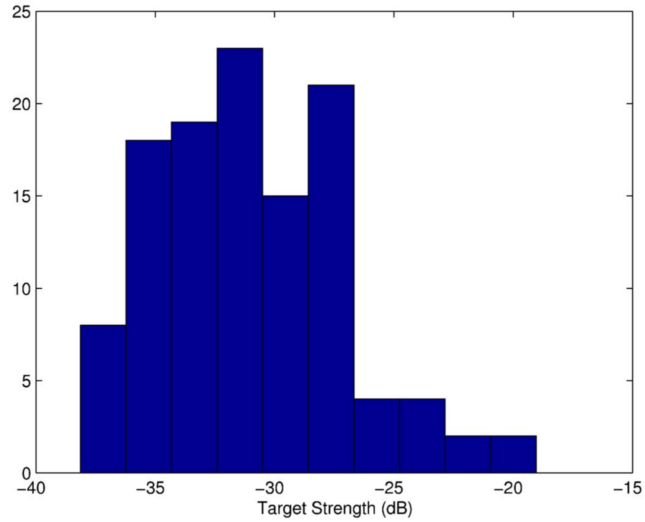

FIG. 4. (Color online) A histogram of "relative target strengths" for the approximate 120 reflections recorded from the animals.

$$\text{TS}_{\text{rel}} = 10\log_{10}\frac{I_{\text{ref}}}{I_{\text{inc}}} = \left(10\log_{10}\frac{I_{\text{inc}}A_{\text{inc}}\rho}{2\pi}\right)\bigg/ I_{\text{inc}} = 10\log_{10}\frac{A_{\text{inc}}\rho}{2\pi}. \tag{4}$$

This equation yields a TS_{rel} of −41 dB for the lateral aspect, the most common orientation for our studies. However, since this expression assumes that the reflected energy is uniformly scattered into the backward hemisphere, the estimate is probably low. The other extreme, that is total specular reflection, neglects the factor of 2π and yields a TS_{rel} of −30 dB, a value more consistent with those observed.

One surprising result of the experiments was that in a large number of cases the reflected energy was unobservable, even though a manatee was clearly in the sonar beam. Since the large air-breathing animals were assumed to reflect a large fraction of the sound, initial impressions of this lack of reflected energy were puzzling. In addition, based on the absorption estimates, as described above, it seemed unlikely that the animal was acting as a sound sink. In lieu of the above tissue measurements, the most likely reason for the

TABLE II. A summary of the reflection coefficients for the various regions.

Reflection coefficient Lateral	CT	OB	OM	IB	IM
Mean	0.129	−0.141	n/a	n/a	n/a
Standard deviation	0.029	0.054	n/a	n/a	n/a
No. of samples (n)	7	7	n/a	n/a	n/a
Dorsal					
Mean	0.113	n/a	−0.072	n/a	n/a
Standard deviation	0.019	n/a	0.006	n/a	n/a
No. of samples (n)	9	n/a	2	n/a	n/a
Ventral					
Mean	0.067	−0.005	0.024	−0.007	0.059
Standard deviation	0.028	0.078	0.053	0.094	0.076
No. of samples (n)	6	6	6	6	6

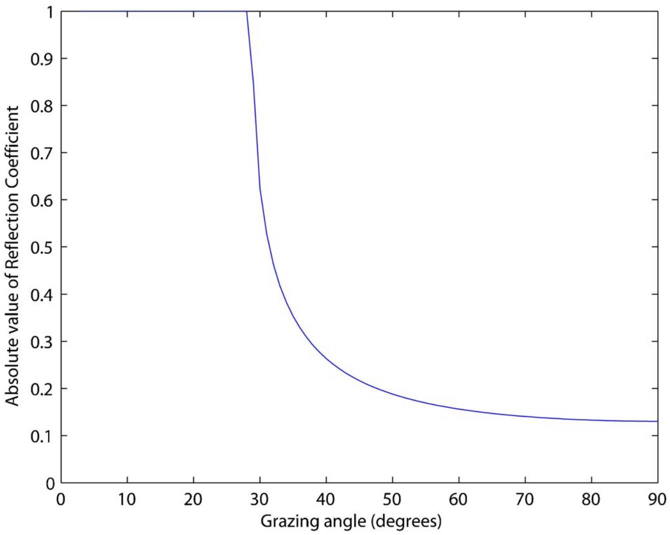

FIG. 5. (Color online) A plot of reflectivity versus grazing angle using Eq. (2) and the data from the lateral umbilicus [1708 m/s and 1149 kg/m^3 (from Table I)] relative to the fresh water sound speed and density measurements in the Sea World manatee pool (1510 m/s and 1000 kg/m^3).

discrepancy is that the animal acts as a specular reflector at the frequency tested. This implies that the sound was reflected, but at an unobservable angle between source and receiver. Future work to confirm this hypothesis would require three-dimensional characterization of the animal's reflectivity. In the context of the observations reported here it is also interesting to note that a report by Dickerson *et al.* (1996) describes the difficulty of obtaining adequate acoustic reflections from the animals. That study was initiated in order to create a manatee detection system in order to prevent deaths in canal locks. The innovative solution considered there was to devise a system that detected the interruption of the acoustic signal, much the same as an electro-optic door opener, in order to detect the presence of the animal and, hence, prevent the locks from closing.

Based on results discussed in this article, a detection frequency of 171 kHz does not appear to be reliable enough to use for detection. Reconciliation of the tissue samples with the observations strongly suggests that the animals' skin acts as a specular reflector, resulting in the reflection of a large part of the signal, but not necessarily back at the observer. Clearly what is needed is a more omni-directional scatter pattern. It is possible that other frequencies might offer a substantial advantage in this regard as the surface of the animal will appear to have different roughness depending on undulations relative to the frequency of incident sound.

Lastly, any true program to detect manatees acoustically should take into consideration the propagation of sound in their native habitat. Shallow water channels with either muddy or smooth rock bottoms present challenging environments in which to work. In this regard, higher frequency systems with narrow beam patterns can be used to minimize interactions with the animals' environment. However, only a truly systematic study of animal reflectivity versus frequency can determine whether active acoustic systems can help to preserve these dwindling marine animals.

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