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Gentle Giants in Dark Waters: Using Side-Scan Sonar for Manatee Research

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Abstract: Manatees are tropical marine mammals that live in a wide variety of aquatic habitats ranging from coastal marine areas to freshwater lakes and rivers located hundreds of kilometers inland. All manatee species are currently characterized as Vulnerable by the International Union for Conservation of Nature (IUCN), primarily due to anthropogenic causes (i.e. poaching, habitat destruction, pollution, collisions with boats) and all of the environments they live in present challenges to biologists and wildlife managers. Tropical freshwater systems are especially difficult to work in because they are generally tannin-stained or turbid and water clarity is very restricted. Locating manatees and observing their behavior in these environments is extremely difficult and is a major limiting factor in determining population parameters. We summarize the use of sonar technology as an aid to detect and study manatees in these freshwater systems. First, by a summary of what has been attempted before our efforts, followed by presenting the various ways we have used this technology in the past 6 years to 1) detect manatees, 2) characterize manatee habitat in ways that would not be possible otherwise, 3) identify mother-calf pairs, and 4) assist in manatee captures. Finally, we discuss the advantages and limitations of using this technology for manatee conservation and research and present directions in which we believe future work can be directed, such as the determination of manatee abundance via distance sampling surveys using side-scan sonar and the use of one of the latest developments in acoustic technology, dual-frequency identification sonar.

Keywords: Manatee, Side-scan sonar, *Trichechus manatus*, Tabasco, Mexico, Freshwater habitat.

1. INTRODUCTION

Manatees (Mammalia: Sirenia: *Trichechus* spp.) are tropical aquatic mammals that live in a wide variety of habitats ranging from coastal marine areas to freshwater lakes and rivers located thousands of kilometers inland (Fig. **1**) [1-2]. Manatees are a typical K-selected species; they have large bodies (480-1400 kg), live a long life (up to 60 years), and produce few offspring (usually one at a time) that take 2-3 years to mature [3]. This ecological strategy is very effective under normal circumstances because manatees have no natural predators and feed on a wide variety of aquatic vegetation [4]. It is likely that manatee populations were historically much larger. In Brazil, manatee population numbers experienced commercial exploitation between 1935-1954, where as many as 4000-7000 individuals were killed per year for meat and hide production [5]. Today manatee numbers in Brazil are not known, but the populations have persisted.

The manatee's unique life strategy however makes them very vulnerable to any disturbance in population numbers because of their slow recovery time. Unfortunately, the ideal habitat for manatees, which consists of shallow calm coastal areas and freshwater rivers and lakes [7], is precisely where humans like to settle. This places manatees at the very crossroads of local human population centers. Currently, all three extant manatee species are characterized as Vulnerable by the International Union for Conservation of Nature (IUCN) Redlist of Threatened Species primarily due to anthropogenic causes [6]. However, the specific threats vary by taxa and geographic location. For example, while the two allopatric subspecies of the West Indian manatee, *Trichechus manatus*, share many threats, they each have unique challenges. The Florida manatee, *Trichechus manatus latirostris*, is primarily threatened by watercraft collisions, drowning in locks and flood-control structures, exposure to cold temperatures leading to cold stress, and intoxication due to brevetoxin (red tide) [8-11]. In contrast the Antillean manatee, *Trichechus manatus manatus*, lives in the perpetually warmer waters of the Caribbean and coastal Central and South America and in areas with much lower densities of motorized boat activity (Fig. **1**). The Antillean manatee, along with the Amazonian manatee, *Trichechus inunguis*, and the West African manatee, *Trichechus senegalensis*, are threaten primarily by poaching, drowning in fishnets, and loss of habitat [12-16]. Today, manatees are found discontinuously throughout their historic range, leaving gaps where their habitat has been sufficiently altered or the local population has been extirpated.

All of the aquatic habitats used by manatees present challenges to biologists and wildlife managers. However, tropical freshwater systems are especially difficult to work in because they are generally tannin-stained or turbid from loose sediment, and water visibility is very poor. These

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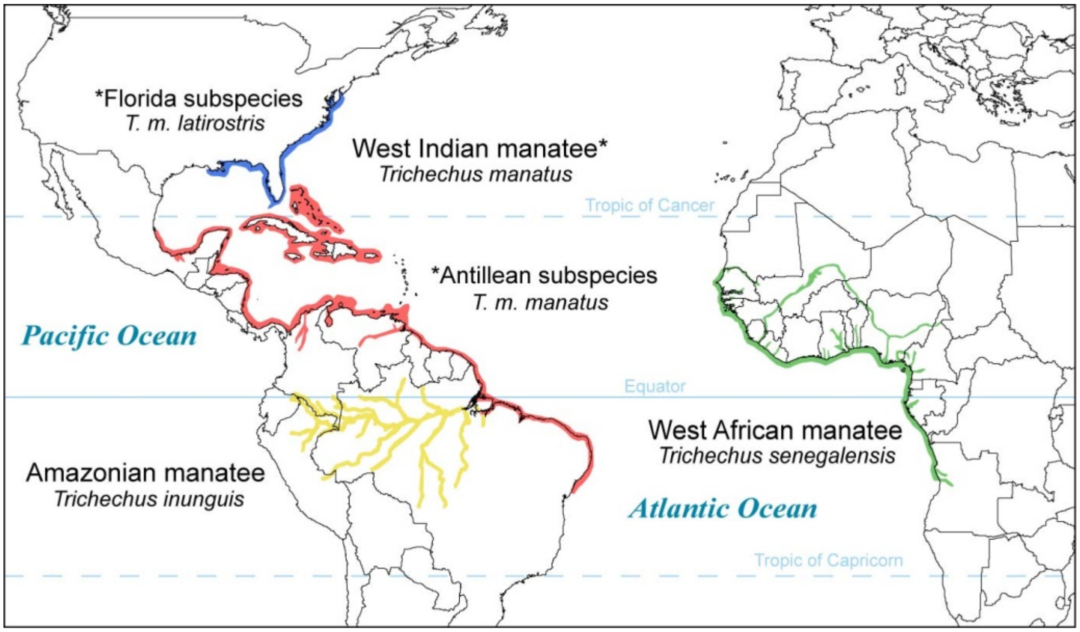


Fig. (1). Geographic distribution of extant manatee species. Range data adapted from IUCN [6].

habitat restrictions are compounded by the behavioral ecology of manatees. In Florida, manatees seek warm water refuges during the coldest months of the year, aggregating in large numbers. The location of these natural and artificial warm water refuges are well known, and are used by biologists to conduct synoptic counts via aerial surveys [17]. However, in the tropics (Fig. **1**), manatees live in warm water year-round and are therefore rarely found in large aggregations. One exception might be manatees trapped in oxbow lakes and deep pools during the extreme dry season in the Amazon and Orinoco River basins [18], however aerial surveys would yield few sightings due to the limited visibility afforded by the dark water. In addition, manatees can be very cryptic, moving slowly and only momentarily revealing the tip of their rostrum when they surface to breathe.

Manatees appear to be arrhythmic, equally resting and being active at any given time of the day or night [19-20]. However, in some locations they appear to avoid activity during the day when they could be more easily observed and tend to feed at night under the cover of darkness [21]. This is especially true in areas of high human disturbance or areas where hunting is common [15, 22]. The traditional forms of locating manatees via aerial and boat surveys, while very useful in certain habitats, yield very low numbers in tropical freshwater systems. Low manatee population densities, small group sizes, cryptic and nocturnal behavior, and poor water visibility are the challenges faced by wildlife managers and biologists interested in studying and conserving manatees in tropical freshwater habitats. It is these challenges that we attempt to face by employing novel sonar technology applications.

In this review we summarize how we have used sonar technology to aid in detecting and studying manatees in these traditionally restrictive aquatic habitats. While we have primarily worked with the Antillean manatee, *T. m. manatus*, the results have relevance to the other taxa living in similar freshwater habitats, the Amazonian manatee, *T. inunguis*, and the West African manatee, *T. senegalensis*. First, a summary of the previous efforts to detect manatees with sonar is given, followed by a summary of the sonar system that we tested and our initial results. Second, we present the various ways we have used this technology over the past 6 years to 1) confirm visual sightings and determine group size, 2) characterize manatee habitat in ways that would not be possible otherwise, 3) identify mother-calf pairs, and 4) assist in manatee captures. Finally, we discuss the advantages and limitations of using this technology for research and manatee conservation applications, as well as present recommendations in which we believe future work can be directed, such as the determination of manatee abundance via distance sampling surveys and the use of one of the latest developments in acoustic technology, dual-frequency identification sonar (DIDSON).

2. PREVIOUS EFFORTS TO DETECT MANATEES WITH SONAR

In the early 1980s several efforts were made to detect manatees using sonar with the primary focus of using this technology to prevent manatee deaths caused primarily by floodgates and canal locks (Matzer and Associates 1980 and American Dredging Company 1983, as cited in [23]). The results were mixed, some reporting good acoustic detection from manatees, while others reported limited success. Complications and limitations reported from these early experiments included high levels of background noise, bottom and surface scatter, turbulence generated by the boat, weak (low amplitude) returns, sonar shadowing, and reduced sonar resolution.

Building on these early studies, Dickerson *et al*., [24] tested the efficiency of 10 different commercial fish finders with the similar aim of creating a manatee detection system in order to prevent manatee deaths in canal locks. The general idea was to develop a system that would automatically stop floodgates and canal lock doors from closing when a manatee was detected, thus preventing it from being crushed. They tested the sonar units on artificial targets (air-filled floats) and on live captive manatees, obtaining good returns from the floats but poor returns from the live animals. Dickerson *et al*., [24] concluded that, while it was possible to detect manatees, the acoustic reflection was not consistent and at times no acoustic reflection was detected [24]. They speculated that the poor detection was likely due to the manatee's fat layer, which might be attenuating the high frequency acoustic signals.

Based on the good target strengths (the proportion of sound that is reflected by the target back to the array) produced by measurements for various marine mammals, including bottlenose dolphins, *Tursiops truncatus* [25], humpback whales, *Megaptera novaeangliae* [26], and northern right whales, *Eubalaena glacialis* [27], there was optimism that manatees would produce a strong target strength. Au [25] experimented with high detection frequencies (23–80 kHz) and found that the target strength produced by dolphins largely depended on body orientation (target strength of the head aspect was 5 dB below that of the broadside aspect) and was greatest in the location between the dorsal and pectoral fins where the lungs are located. This area of the body exceeded the minimum target strength recorded by the tail aspect by 21 dB [25]. Once again this seemed favorable for manatee detection because they have large elongated lungs that are positioned dorsally along the long axis of the body [28], potentially providing an excellent acoustic target.

In 2001, in light of the growing number of manatee deaths per year caused by watercraft collisions, the Florida state legislature appropriated funds for the Manatee Avoidance Technology Program. The primary main goal of this program was to fund technological solutions to address the conflict between manatees and watercraft [29]. One idea was to develop a "manatee finder" that could automatically alert boaters of the presence of manatees so that they could take the appropriate precautions (mainly slowing down). Delays in obtaining research permits from the U.S. Fish and Wildlife Service have thus far prevented field testing on wild manatees in Florida [23].

However, with appropriated funds, Jaffe *et al*., [30] measured the acoustic reflectivity of the Florida manatee using a detection frequency of 171 kHz on both captive animals and manatee carcass tissue. They reported that the majority of the reflections from live manatees were between –32 and –35 dB, however, a substantial portion were below -48 dB, which was their detection threshold due to ambient noise [30]. In addition, an acoustic reflection was not always observed in spite of the manatees crossing right in front of the sonar beam. Jaffe *et al*., [30] report that while substantial reflections can be recorded from live manatees, the values are at times much lower than the empirical target strengths predicted. However, analysis of the manatee tissue ruled out the previous hypothesis [24] that manatee fat layers acted as an acoustic sink. Jaffe *et al*., [30] also concluded that the manatee's skin may act as a specular reflector at the 171 kHz frequency they tested, possibly reflecting the acoustic signal in an unobservable angle. This may partially explain why previous efforts to detect manatees in the wild with sonar have had mixed success [24] .

3. THE USE OF SIDE-SCAN SONAR

Side-scan sonar systems function by emitting a narrow fan-shaped pulse at a wide-angle perpendicular to the movement of the sensor (see Fig. **2**). The transducer and sensor are either towed in a torpedo-like capsule "towfish" connected by a cable or mounted directly onto the vessel. Since side-scan sonar systems became commercially available in the late 1960s, they have been used for a variety of purposes including: detection of submerged objects and features for the marine industry and maritime archaeology [31], bathymetric relief mapping [32], and characterization of sea floor material [33]. In addition, side-scan sonar has been used to infer on animal behavior from benthic features such as sediment scars left by feeding gray whales, *Eschrichtius robustus* [34] and walruses, *Odobenus rosmarus* [35].

In 2005 we tested a high frequency (262-455 kHz) side-scan sonar unit developed by Humminbird® (Model 987c SI, Johnson Outdoors Inc., St. Racine WI, USA; see Table **1**) in three locations that represented different freshwater habitats ranging from clear water in Florida to dark tannin-stained water in Honduras and Mexico [36-37]. Our goal was to develop an alternative method for biologists and wildlife managers to detect manatees in dark tannin-stained freshwater habitats to assist in research efforts. All previous attempts to use sonar to detect manatees were with stationary or downward facing echo sounder systems [24, 30]. To the best of our knowledge our experiments were the first to apply side-scan sonar to detect manatees.

3.1. Technology and Image Interpretation

The Humminbird® fish finders equipped with side-scan sonar come with 3 or 4 sonar beams; two downward facing echo-sounders producing 83 and 200 kHz (50 and 200 kHz on legacy models), and one or two narrow side beams producing 455 and 800 kHz (262 and 455 kHz on discontinued models; Table **1**). The two narrow side beams are positioned at different angles, with the lower frequency offering a reported total coverage of 180° (Fig. **2**). All subsequent models have replaced the 262 kHz beam with the 455 kHz and added an 800 kHz beam at the lower angle (Table **1**). One or both of the downward facing echo sounder frequencies can be operated at the same time, while only one side beam frequency can be used at any one time. Downward sonar beams provide real-time depth data when the side-scan sonar images are displayed on the screen.

The Humminbird® transducer is directly attached to the boat (transom-mounted) and is not dragged or towed as in other side-scan sonar units. This means that the sonar beams are emitted just below the surface of the water, providing more coverage of the water column in shallow areas. Units are powered by 12 V batteries and have a power draw of 615-1300 mA depending on the model. These sonar systems come with a built-in screen and therefore do not require the addition of a laptop or monitor to view acoustic images. The screen size of the unit depends on the model and ranges from 12.7-26.4 cm. The image on the screen can be captured in real-time using one of the action buttons on the unit and saved as a .png file or a .bmp file in the discontinued models (Fig. **3**). Screen captures are saved on a secure digital (SD) memory card that is sold separately. In addition, scan

Table 1. Technical Specifications of Humminbird® Units Equipped with Side-Scan Sonar

Humminbird® Fishfinder Model				
	981c SI*	987c SI*	797c2 SI*, 798c SI* 798ci HD SI	898c SI, 997c SI*, 998c SI, 1197c SI*, 1198c SI
Side-scan sonar				
Beam frequency and angle	262 kHz (2) 84° at -10 dB	262 kHz (2) 84° at -10 dB 455 kHz (2) 40° at -10 dB	455 kHz (2) 86° at -10dB	455 kHz (2) 86° at -10 dB 800 kHz (2) 55° at -10 dB
Total coverage†	180°	180°	180°	180°
Max depth (m)	30.5	30.5	45.7	45.7
Lateral range (m)	73	73	73	73
Echo sounder sonar				
Beam frequency and angle	50 kHz 74° at -10 dB 200 kHz 20° at -10 dB	50 kHz 74° at -10 dB 200 kHz 20° at -10 dB	83 kHz 60° at -10 dB 200 kHz 20° at -10 dB	83 kHz 60° at -10 dB 200 kHz 20° at -10 dB
Max depth (m)	762	762	457	457

*Legacy models

†Coverages reported by the manufacturer (Installation and Operations Manual for: 981c SI & 987c SI; 997c SI; 898c SI & 998c SI; 1197c SI; and 797c^2 SI. Available from URL http://www.humminbird.com/support/ProductManuals.aspx)

sequences can be recorded as a .son file and saved on the SD card.

In newer models, screen captures and recorded sequences can be viewed again on the unit, however, the scan sequence can also be observed at a later time on a PC using side-scan sonar viewer software such as HumViewer® (v.67 available free at http://humviewer.cm-johansen.dk/) and YellowFin® viewer (v.2). To view recorded files on the YellowFin® viewer, files must first be converted to a .872 file using a file converter (HBSI® converter v.1.0.3 available free at www.sideimagingsoft.com/downloads/ HBSI_113.msi). HumViewer® does not need a file converter and allows for various manipulations such as: changing the brightness and contrast, creating a movie recording, creating screen captures in either .jpg, .png, or .bmp, exporting trackways and waypoints as .kml, .gpx, or .cvs, showing the track where the recording was done, and some calculations of measurements of length

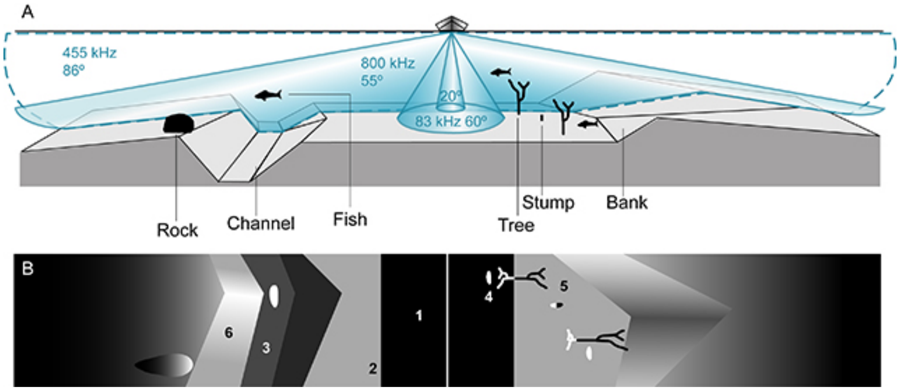
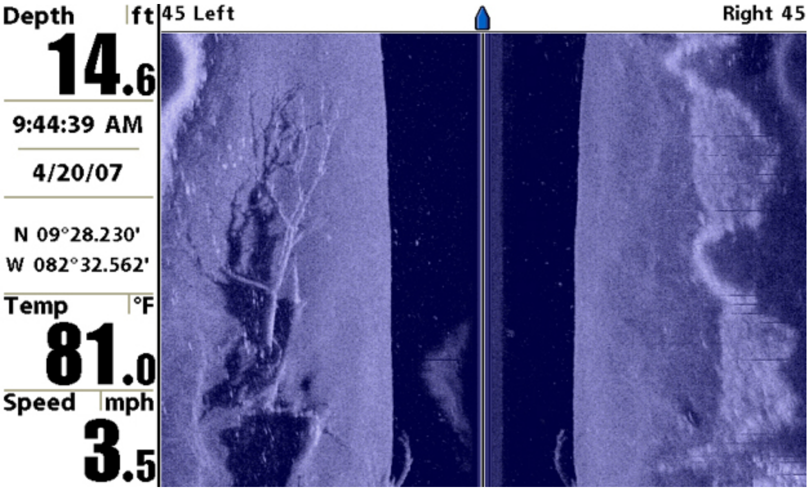


Fig. (2). Sonar beams of Humminbird® 998c and interpretation of side-scan sonar acoustic image. **A)** Two narrow side beams of 455 kHz (total coverage of 180°) and 800 kHz (total coverage of 110°) and two echo-sounder beams of 200 kHz (20° coverage angle indicated by center cone) and 83 kHz (60° coverage angle indicated by outer cone). **B)** The acoustic signal is displayed in a conveyor belt fashion, with the latest response as the top horizontal line. As the boat moves in a linear direction new sonar lines are added. In this model, the boat is moving away from the reader. The components of the side-scan sonar acoustic image consist of the water column (1), which appears as a dark area between the midline and the bottom return (2). Channels (3) appear darker because of the lack of an acoustic reflection. Objects, such as fish (4) in the water column appear bright white. Objects on or near the bottom produce a shadow (5) because of the blocked signal. Rising areas such as banks (6) appear brighter due to the increased target strength. Image modified from Gonzalez-Socoloske *et al.* [37].



Depth ft 14.6

9:44:39 AM

4/20/07

N 09°28.230'
W 082°32.562'

Temp °F 81.0

Speed mph 3.5

Fig. (3). Full screen capture from Humminbird® 998c in San San Pond Sak, Panama displaying the left and right side of the side-scan sonar acoustic image. Note the submerged tree on the left side resting on smooth substrate. Additional parameters recorded on the screen capture include: water depth, date and time of day, geographic coordinates, water temperature, and speed. Side-scan sonar is producing at 455 kHz with a lateral range of 45 ft and the echo sounder is producing at 200 kHz.

and distance to detected objects.

The unit display can be toggled between viewing the left or right side, or can display both sides of the side-scan sonar response simultaneously. In addition, half the screen may be used to view the conventional echo sounder response or a map while viewing the side-scan sonar response. Various customizable parameters can be displayed on the screen simultaneously including: water depth, time of day, date, geographic coordinates, vessel speed (determined via the built-in geographic positioning system [GPS]), surface water temperature, and heading (see Fig. **3**). Note that these parameters may not be representative of the whole image, but rather reflect the moment of the screen capture which is represented by the last horizontal line on the top of the sonar image.

Side-scan sonar images consist of a right and left side divided by a dark section in the middle representing the water column directly beneath the boat (Figs. **2B** and **3**). The middle line represents the trajectory of the vessel, with the location of the vessel situated at the top center of the image. As the vessel moves in a straight line new acoustic data is added to the top of the image and older data is pushed down in a top to bottom conveyor belt fashion. On either side of the central water column is the bottom return, the point where the first acoustic signal is reflected by the bottom surface. This point lies directly below the boat and objects detected at the bottom below the boat will be observed on both sides of the acoustic image. The rest of the acoustic image to the left and right sides can be interpreted as the bottom surface return continuing laterally away from the boat until the end of the lateral range.

Objects detected within the water column situated below the boat will appear in the dark section next to the midline. Objects detected further laterally will appear within the bottom response. Objects and surface features appear in shades from bright white to dark blue depending on the density of the material. Dense objects, with large target strengths, appear white, where as shadows, which have no target strength because the signal has been blocked, appear dark blue (Figs. **2** and **3**).

For the best acoustic images, boat speeds between 2.5 to 7.0 km hr^{-1} are recommended. The speed of the vessel or the swimming speed of the target can alter the relative size of features detected by the side-scan sonar, faster speeds make objects look smaller along the plane perpendicular to the sensor, while slower speeds make the objects look bigger. To properly compare screen images it is important to maintain similar vessel speed between trials. In addition, the water column can take up a disproportionate amount of the sonar image depending on the water depth. For example, if two screen captures have a lateral range of 10 m, but one has a water depth of 1 m and the other of 5 m, the first image will have 9/10 (only 1 m is used for the water column) of the "image space" for the 10 m benthic response, while the second will have to adjust the image so that the 10 m of benthic response fit in only ½ the image (due to the 5 m water column). Supplemental data (e.g. boat speed, water depth, etc.) of all side-scan sonar images presented in this manuscript can be found in the **Appendix**.

3.2. Manatee Detection and Image Model

We conducted experimental trials using side-scan sonar in Crystal River, Florida (28.888°N, 82.590°W) and in a freshwater lake in Tabasco, Mexico (Laguna de las Illusiones [LDI], 18.011°N, 92.931°W), where manatees could be detected visually. Trials consisted of a short transect through an area known to have manatees present and utilized a visual observer and a sonar observer. For each trail each observer noted the number of manatees observed, side of the boat detected (left or right), and the approximate distance from the boat. Based on 29 trials in LDI and 14 trials in Crystal River, we estimated a detection frequency between 81-93% [37].

During our experiments in Mexico and Florida, no negative behavioral effects were observed when the sonar was used. Manatees have a functional hearing range between 0.4 and 46 kHz, however maximum sensitivity is between 6

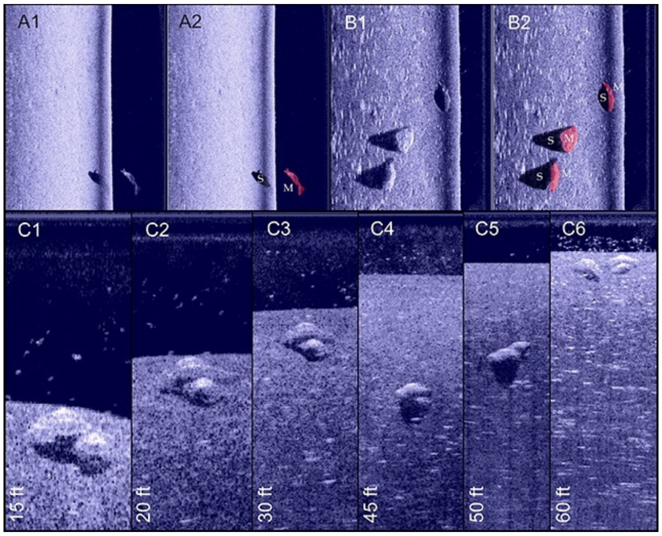


Fig. (4). Side-scan sonar images of Antillean manatees. All images are from the wetlands of Tabasco, Mexico. Figure symbols: manatee (M), shadow produced by manatee (S). A1) Screen capture of left side of sonar image of an adult manatee directly below the boat swimming down towards the bottom. A2) Digitally-enhanced interpretation of A1 highlighting the acoustic response of the manatee body (red) and the shadow produced (gray). B1) Screen capture of left side of sonar image of three adult manatees. B2) Digitally-enhanced interpretation of B1 highlighting the acoustic response of the manatee bodies (red) and the shadows produced (gray). C1-C6) Screen captures from left side of sonar image of a mother-calf pair, except C6 which includes an additional adult manatee, with the side-scan sonar range between 15-60 ft (4.6-18.3 m). Images for C1-C6 have been cropped along the axis of boat travel and rotated counterclockwise 90 degrees to highlight how the manatee acoustic image and the proportion of the water column and bottom response change with increasing side-scan sonar range.

and 20 kHz [38]. Above 26 kHz hearing sensitivity drops about 40 dB per octave and 20 dB per octave below 0.8 kHz. For manatees to hear sounds in these ranges, sounds must be produced much louder, around 90 to 100 dB [38]. However, in the off chance that manatees could detect the 50 kHz frequency, we did not use it on the echo sounder during our experiments and only used frequencies greater than 200 kHz.

Manatee detection depends on target distance from the transducer and target orientation. Manatees can be clearly distinguished at a lateral distance of between 5-20 m (Fig. **4C**). Manatees are difficult to distinguish with lateral ranges greater than 20 m. The tail appears to produce the least response when ensonified, and the area of the anterior-mid dorsal, where the lungs are located, gives the best response (Fig. **4**). This correlates well with the target strength data from dolphins obtained by Au (1996). The shadow produced by the large body of the manatee is the most telling feature of the acoustic response (Fig. **4**). In general, manatees appear as a large oval object with a corresponding shadow that is triangular in shape with rounded edges (see Fig. **4**). At times, no acoustic image is produced from the manatee body but the shadow is still visible (see Fig. **7D**).

Based on manatee body orientations in relation to the direction of the sonar sensor, we created a simple model of how ensonified manatees appear on the side-scan sonar acoustic image of the Humminbird® units (Fig. **5**). These experiments were conducted in Crystal River, Florida, where we could note body orientation as the sonar passed due to the clear water. Acoustic images in the model were created with actual side-scan sonar images of manatees with known body orientation and distance from the boat [36].

If a manatee is detected on the top of the water column and is located close to, or immediately under, the boat, the acoustic response will be in the dark area (representing the water column) near the white middle line (Fig. **5A**). The corresponding shadow will be on the far side. If the manatee is at the bottom of the water column, then it will appear completely or partially in the dark area with the shadow closely associated and separated by a small gap (Fig. **5B**). If the manatee is located in between the surface and the bottom and the body orientation is vertical or at an angle, the corresponding acoustic response will reveal that and the shadow will appear at an in-between distance (Fig. **5C**). If the manatee is perpendicular to the boat, the acoustic response will be minimal or absent and the shadow will have a horizontal shape (Fig. **5D**). If the manatee is located parallel to the boat the shadow will be on the opposite side and will have a triangle shape reflecting the general shape of the manatee as its body tapers at both ends (Fig. **5E**). Finally, if a mother and calf are present and parallel to the boat, they will both only be visible if the calf is in front of the mother in relation to the boat or there is sufficient space between them (Fig. **5D**). Animals that are at an angle relative to the boat will have a slanted shadow. Relative distances from the boat can be observed in the acoustic response.

4. CURRENT USES OF SIDE-SCAN SONAR FOR MANATEE RESEARCH

Most of the data we present in this section are from the lakes and rivers of the wetlands of Tabasco, Mexico (WTM; 18.041°N, 92.236°W); however, data are presented from three other representative freshwater sites with dark water: Wetlands of San San Pond Sak, Panama (9.524°N, 82.510°W), Tortuguero National Park, Costa Rica (10.501°N, 83.493°W), and Cuero y Salado Wildlife Refuge, Honduras (15.782°N, 87.091°W). In Tabasco, Mexico, the Grijalva-Usumacinta basin is one of the largest freshwater wetland systems in the world. Manatees have been recorded

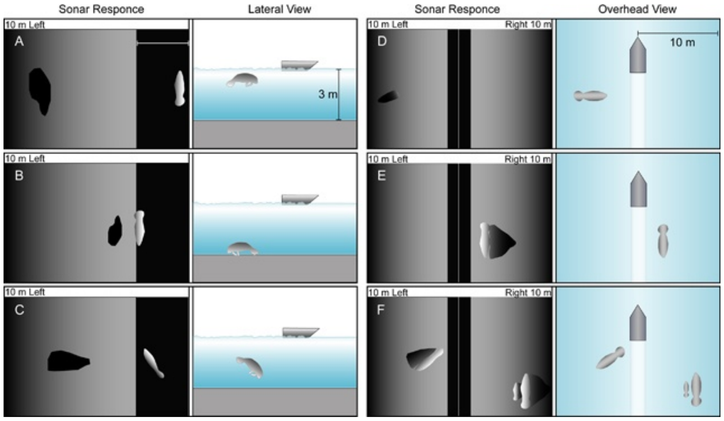


Fig. (5). Model of acoustic images of manatees produced by side-scan sonar in relation to manatee location and body orientation. Image adapted from Gonzalez-Socoloske [36].

through carcasses, interviews, and recent sightings throughout this extensive riverine system (Olivera-Gomez unpublished data). The manatee population in this area may be the most important in Mexico in terms of population size, however, research in this area is very arduous due to the difficulty of observing manatees in this habitat.

There are currently four ways in which we are using side-scan sonar technology to aid in manatee research in these dark tannin-stained freshwater systems: 1) confirmation of visual sightings and determination of group size, 2) determination of mother-calf pairs, 3) habitat characteriza-tion, and 4) assisting manatee captures (Fig. **6**).

4.1. Sighting Confirmation and Determination of Group Size

One of the most important uses of this technology at the moment is sighting confirmation after visual or trace detection and the determination of group size. During boat surveys in freshwater rivers and lakes, manatees may be detected visually on rare occasions; however, the sighting may be very brief and could be confused with other fauna (river otters or even large fish). Most of the time manatees are indirectly detected by the ripple pattern produced by their tail (sometimes referred to as a “footprint”) or other disturbances generated by the animal.

In some lakes in Tabasco, Mexico, when the conditions are just right and the water surface is very calm, manatees leave characteristic bubble trails as they move along the bottom substrate “walking” with their pectoral flippers (see Fig. **6B**). The bubbles are produced as gas is released from the bottom substrate as the manatees disturb the bottom. In other occasions, manatees may be detected by sound as they feed on floating vegetation (e.g. *Pistia stratiotes* or *Eichhornia crassipes*). Observing the manatees is nearly impossible because they often feed under mats of floating vegetation where their nostrils are obscured during respirations.

In all of these cases, we have found that using side-scan sonar can help to confirm if the suspected target is indeed a manatee. In addition, using this technology can reveal the number of individuals. On many occasions where we have visually detected only one manatee, the sonar images revealed two or three (Fig. **7**). Manatees do not surface synchronously, so determining how many are actually in a group using visual cues alone is often very difficult.

Fig. (6). Uses of side-sonar in manatee research. **A)** Typical manatee sighting in dark waters only revealing the tip of the snout. Laguna de las Ilusiones [LDI], Mexico. **B)** Characteristic bubble trails created by manatees in areas with the right bottom conditions. LDI, Mexico. **C)** Typical manatee habitat in freshwater tropical riverine systems. Cuero y Salado Wildlife Refuge, Honduras. **D)** Mother-calf pair. San Pedro Creek, Balancan, Mexico. **E)** Technique used to capture manatees in dark waters. LDI, Mexico. **F)** Picture of the authors with an adult manatee captured in June 2011. Laguna San Jose del Rio, Balancan, Mexico. All images courtesy of the authors.

4.2. Habitat Characterization

From the surface many of the riverine habitats look similar (see Fig. **6**). Using side-scan sonar we are able to determine bottom contour, texture, and depth, which can all play a role on how manatees use an area. We have found that we can distinguish between several bottom substrate types (Fig. **8**).

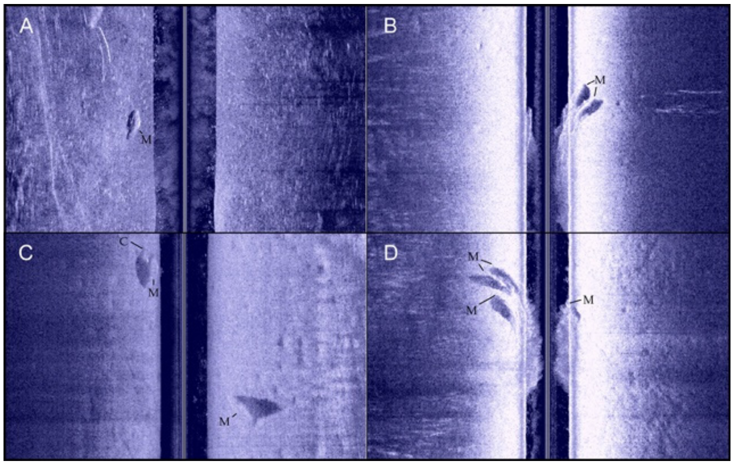


Fig. (7). Sighting confirmation and determination of Antillean manatee group size using side-scan sonar. Figure symbols: manatee (M), manatee calf (C). **A)** Screen capture of one adult manatee. **B)** Screen capture of two adult manatees. **C)** Screen capture of three manatees, one adult and calf on the left side and one adult on the right side. **D)** Screen capture of four manatees, three adults on the left side and one adult on the right side. Note the sediment plums created by the manatees.

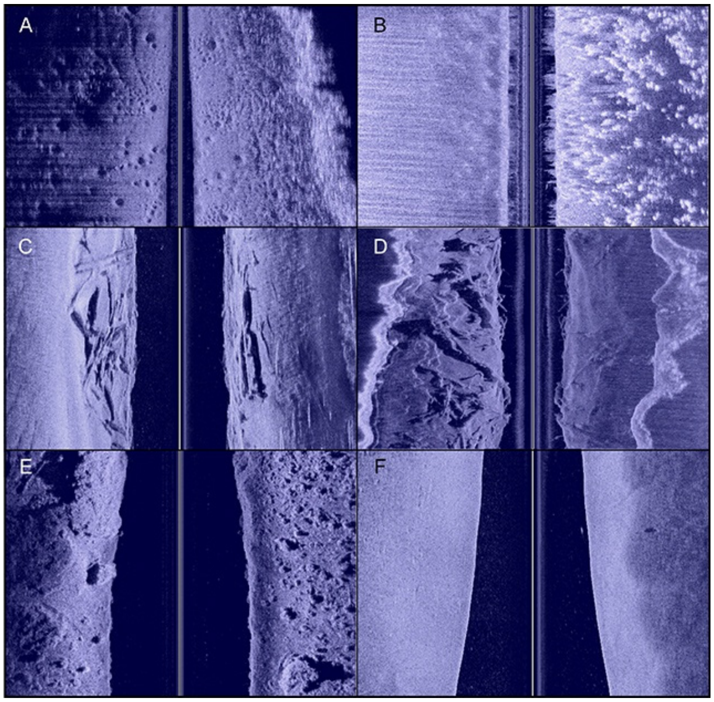


Fig. (8). Habitat characterization using side-scan sonar. Representative screen captures of various habitats in freshwater systems. **A)** Shallow bottom with small to medium sized holes on the soft sediment. Laguna de las Ilusiones, Mexico. **B)** Underwater vegetation. Tabasco, Mexico. **C)** Submerged logs on otherwise smooth bottom sediment. Tortuguero, Costa Rica. **D)** Submerged branches partially covered with sediment. San San Pond Sak, Panama. **E)** Hard rocky bottom substrate. Tortuguero, Costa Rica. **F)** Smooth sediment with no rocks, vegetation, or branches. Tortuguero, Costa Rica.

In freshwater systems we can distinguish between smooth versus irregular bottoms, often scattered with objects such as submerged logs and branches (Fig. **8**). We can also determine the presence or absence of underwater vegetation, especially in areas where the lake and river levels rise 6 m during the rainy season, submerging vegetation that would not otherwise be found in the water (Fig. **8B**). All of these characteristics are useful in determining habitat preferences that manatees might have. In addition, natural holes and depressed areas can be detected and are commonly preferred by resting manatees (see Fig. **9D** and **9E**). In the coastal marine waters of Belize, this technology was used to characterize and survey manatee resting holes during the day and night [39].

4.3. Identification of Mother-Calf Pairs

The identification of mother-calf pairs can be important for studies of population dynamics and reproduction. While it is impossible to determine the sex of the detected manatee using sonar, we can infer adult females from mother-calf pairs by the relative size of the manatees in the acoustic response and the close proximity of the calves to their mothers (Fig. **9**). These mother-calf pairs have been confirmed both visually (Fig. **6D**) and through live captures.

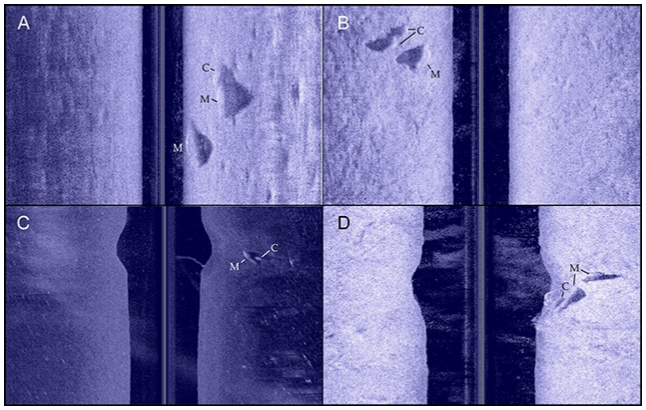


Fig. (9). Identification of Antillean manatee mother-calf pairs using side-scan sonar. Figure symbols: manatee (M), manatee calf (C). **A)** Screen capture of two adult manatees and one calf. Laguna de las Ilusiones [LDI], Mexico. **B)** Screen capture of one adult manatee and two calves. LDI, Mexico. **C)** Screen capture of manatee mother-calf pair. Wetlands of San San Pond Sak, Panama. **D)** Screen capture of two adult manatees and one calf in a natural hole. LDI, Mexico.

As noted earlier, the size of the object can be influenced by several parameters (e.g. boat speed and lateral distance to target); however, when more than one manatee is detected at the same time, their relative size can be compared with each other because many of the factors remain constant. Typically, calves appear to be up to half the size of adult manatees and are generally very closely associated with the adult manatee (Fig. **9**). To insure that an adult manatee is not being detected with a perpendicular body orientation (thereby appearing much smaller) several passes may be necessary (see image sequence in Fig. **4C**). These will also confirm the association between mother and calf, as most unrelated adults tend to disperse in different directions when disturbed.

4.4. Assistance in Capture Efforts in Dark Waters

Scientists capture manatees for a variety of reasons, from health assessments to applying radio tagging devices to understand movement patterns [40]. However, manatees are extremely difficult to capture in turbid and tannin-stained water systems. The main reason is that it is very difficult to detect them.

Most manatees have been captured in marine or brackish waters using a method involving sighting the target manatees from a raised platform on a boat or from aerial reconnaissance and then pursuing the manatee until it can be safely surrounded by a net. However, this methodology is not very successful in dark water. A weeklong manatee capture effort in Tortuguero National Park, Costa Rica, in 2005 was unsuccessful due to the difficulty of locating manatees in the riverine habitat (C. Espinoza pers. comm.). An alternative method in dark waters is to bait manatees into a location that can be enclosed once they enter, as was the case in 2008 in the Wetlands of San San Pond Sak, Panama [41]. However, this was only possible because manatees accepted banana leaves and sought them out over other available vegetation.

We have used side-scan sonar to assist in net captures of manatees in several locations in Tabasco, Mexico, ranging from river systems to land-locked lakes (Fig. **10**). Once a manatee is detected, either visually or by the sonar, a net is dropped around the sighting location encircling the target animal (Fig. **6E**). Once this is done, a second boat scans the area to determine if the manatee is still within the net (Fig. **10**) or if it has escaped. For this technique to work, manatees have to attempt to escape by heading in any direction and entering and entangling in the folds of the net. If they remain within the circle they cannot be captured with this technique. Some manatees that have been previously captured remain very still in the center of the net circle and do not try to escape. In these cases the sonar is very valuable because it can confirm that they are still within the confines of the net and the capture team to continue trying to get the manatee to flee towards the net. The boat with the sonar does not have to be within the net circle because the sonar beams are able to penetrate through the net (Fig. **10**).

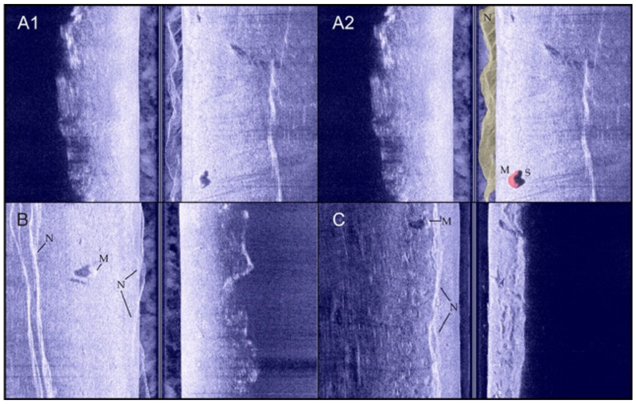


Fig. (10). Assistance in Antillean manatee captures in dark waters using side-scan sonar. All images are from Laguna de las Ilusiones, Mexico. Figure symbols: manatee (M), shadow produced by manatee (S), capture net (N). **A1)** Screen capture of an adult manatee behind the capture net. **A2)** Digitally-enhanced interpretation of A1 highlighting the capture net (yellow) in the water column and the manatee (red) and shadow produced (gray). **B)** Screen capture of an adult manatee surrounded by the capture net. **C)** Screen capture of an adult manatee behind the capture net.

5. ADVANTAGES AND LIMITATIONS

The use of side-scan sonar for detecting manatees offers scientists and wildlife managers with various advantages, however, this technology also comes with limitations. Some limitations are specific to the Humminbird® units, while others pertain to the side-scan sonar technique in general or the behavior of the target animals (Table **2**).

5.1. Equipment and Technology

One of the major advantages of the Humminbird® sonar systems is that they are compact and can be transported in a waterproof hardcase with relative ease. This makes them useful as a tool in remote areas where larger units would be cumbersome to transport. However, we have found that the cable connections can be rather weak and can break over time. It is recommended that during installation and removal of the sonar system, extra care be taken to not bend the cables at the ends where they connect to the unit or the transducer.

Table 2. Summary of Advantages and Limitations of Using Side-Scan Sonar for Manatee Research

Advantages	**Limitations**
Humminbird® sonar systems	
Compact units, with built-in screens	Weak cables can break after repeated use
Additional data (see Fig. **3**)	Screen size and image resolution
Affordable, can be shared between groups	Glare on screen during sunny days
Records screen captures and scans	
Transom-mounted transducer	
As a technique for manatee surveys	
High detection rate (>80%)	Detection range of <20 m (40 m swath)
Greatly reduces availability bias	Limited to line surveys at constant speeds
Allows for night surveys	Limited to perpendicular detection
	Small spatial scale vs. aerial surveys
	Possible false positives and false negatives
Manatee behavior	
Sedentary lifestyle	Manatees moving out of detection range

The built-in screen is both an advantage and a limitation. The built-in screen eliminates the need for a monitor or laptop to visualize the acoustic images and the need for additional cables to connect them, thereby simplifying the use of the system. However, the screen on the smaller units (700 series) can be rather small and on bright days the glare from the sun makes it challenging to see the images on the screen. In addition, having an external monitor or laptop might allow for additional real-time analysis of the acoustic image. Units do have the capability to record both screen captures and scan sequences on to memory cards, thereby allowing for analysis of the acoustic images on a computer at a later time.

Compared to other side-scan sonar systems, Humminbird® units are relatively cheap ($1,000-3,000 USD), which makes it feasible for small non-government organizations (NGOs) and protected area managers to purchase them and use this technique for surveys. In addition, Humminbird® units use transom-mounted transducers allowing for them to be used in very shallow water (<1 m) and offering a greater total coverage than other side-scan sonar units towed in a "towfish" assembly. Many of the freshwater systems used by manatees are shallow (<10 m) and have submerged trees, logs, and rocks that would make the towfish system prone to entanglement (Fig. **8**).

5.2. Interpretation of Images and Scale of Survey Area

As a survey technique, side scan sonar provides several advantages over aerial and visual boat surveys in certain habitats. Aerial surveys are not feasible in many dark freshwater systems because of the narrowness of the river and the overhanging vegetation. In addition, availability bias [42] is much greater because manatees have to be on or very near the surface of the water before they can be sighted. As an example, no manatees were sighted during a four hour 750 km long aerial survey by the authors under good viewing conditions of the Usumacinta River and surrounding lakes in early January of 2009, although we have confirmed through captures that there were at least 20 manatees in just one of the small lakes that was surveyed (Olivera-Gomez unpublished data).

However, like other boat-based surveys [43], side-scan sonar surveys are small in scale compared to aerial surveys. Surveys are limited to areas that permit constant speeds between 2.5-7 km h^{-1} and travel in a linear direction. Detection is only possible perpendicular to the sonar sensor at a maximum range of 20 m on either side of the boat. Like other survey types, observer experience is important and viewer fatigue can be an issue after prolonged observation. Because manatee detection is not automated and is judged by the observer, there is a possibility of both types of perception bias [42]: false positives, confusing a log or other object for a manatee, and false negatives, failing to detect a manatee in the sonar image (Table **1**).

5.3. Behavior of Manatees

Manatee behavior may play into detection success with the use of side-scan sonar. Because detection is only possible perpendicular to the boat, it is possible that manatees may move out of the detection range before the boat passes them. Manatees are known to avoid boats [44], however some argue that they have trouble hearing the low frequency sounds produced by boat motors [45], which may provide a partial explanation for the high number of manatee-boat collisions in Florida.

We have found that manatees appear to behave differently in the dark water rivers versus dark water lakes. In shallow lakes, manatees appear to remain very still near the bottom when approached by the boat, even if passed as close as 1 m. In contrast, in the river systems, manatees appear to avoid the boat and swim away towards the shore of the river or towards the deeper section in the middle. This difference in behavior makes detecting manatees in lakes much easier using this technique. The best sonar images of manatees are when they remain relatively motionless as the sonar beam passes them (see Fig. **4**).

6. FUTURE RESEARCH

We are just beginning to explore the possibilities of using sonar technology in manatee research. As technology advances, and more experiments are conducted, we envision this technology being used by scientists for determining population density and abundance estimations and extending into other areas of interest such as manatee behavior studies.

6.1. Using Side-scan Sonar

The most pressing needs at the moment, beyond detecting manatees, is the ability to estimate population numbers for a given area (population density and abundance). This is the most sought after statistic by wildlife managers, yet it has been a challenge to manatee researchers in most countries, including areas where aerial surveys provide reliable counts. This uncertainty is primarily due to the high variability of detection rates in various habitats and under different environmental conditions. Many factors can influence detection during aerial surveys such as weather, flight speed and altitude, observer experience, glare, water visibility, and sea state [46-47]. Much of the same is true for visual boat and land-based surveys [43].

The main limiting factor is the unknown detection rate. If a detection function could be estimated with confidence, then manatee density could be estimated by correcting for the error. Side-scan sonar does not eliminate all of the factors associated with detection rate, however, it does narrow some of them down. Through the use of marked manatees in a semi-controlled environment, detection rates could be calculated for various conditions. Using distance sampling techniques [48] could be an option because side-scan sonar works in linear transects at a constant speed and manatee detection is only possible exactly perpendicular to the transect line. In addition, it is possible to estimate (at least categorically) the distance of the manatee from the transect line. Careful tests are needed to estimate the accuracy of the lateral distance estimation of objects from the sonar images using software such as HumViewer®.

Another potential direction for future research is to use pattern recognition software to analyze side-scan sonar images so that manatee detection can be automated and thus reduce user bias. Once a large database of the acoustic images of manatees is amassed, the manatee response could be characterized digitally and the software could be tested with control images with known manatee presence and absence to determine detection accuracy. Ideally, this type of software would be used while conducting the survey in real time, however, the Humminbird® units may limit this due to the built-in screens and the need to upload saved images and videos to a computer before further analysis and manipulation.

6.2. Using other Kinds of Sonar

Some of the limitations of side-scan sonar (i.e. the boat must be moving in a linear direction and only lateral detection) could be overcome with other types of sonar systems. The use of dual-frequency identification sonars (DIDSON) has great potential. DIDSON operates at two frequencies and uses acoustic lenses to both receive and transmit very narrow beams of sound. The advantage of these systems is that the acoustic image is more like a movie compared to the still image produced by side-scan sonar [49]. In addition, they can be used while the vessel is in motion or stationary and they can be pointed in any direction. Moving objects can be tracked and potential manatee behavior could be observed with these kinds of sonar systems.

DIDSONs are typically mounted on remotely operated vehicles (ROVs) to search and explore areas of zero visibility. However, recently they have been employed with relative success in key stationary locations to track spawning and migrating Sockeye salmon, *Oncorhynchus nerka*, and steelhead trout, *Oncorhynchus mykiss* [50, 51]. A similar technique could be used to track and count Amazonian manatees at key locations during their annual dry season migration from the receding waters of the river systems into deep-water lakes [18].

The major limitation with these kinds of sonars to manatee biologists is the high cost, currently well above $20,000 USD, plus the cost of all the necessary accessories (laptop or monitor, software, cables, etc.). However, the kind of data they would provide may be worth the expense in some cases. The preliminary results from testing a DIDSON (1.1 and 1.8 MHz) for manatee detection in Florida are encouraging [52].

CONCLUSION

Manatees can be difficult to detect in all the different environments they inhabit, however, dark water rivers and lakes (i.e. tannin-stained or turbid) pose the most difficulty to scientists and wildlife managers. In many such locations, manatee research and conservation efforts have been severely limited due to the elusiveness of this genus. Confirmation of continued existence has only been possible through anecdotal reports from interview surveys and rare cases of manatee mortality. It is in these systems that the use of an alternative detection method has the most value.

The results of our initial experiments with side-scan sonar revealed that manatees could be detected at high rates (> 80%) within the range of the sonar, both in clear and dark water systems. Knowing that manatees could be detected with side-scan sonar opened the possibility for this technology to be used in various ways to assist in conservation and research efforts.

Currently, there are four ways in which side-scan sonar is being applied in these systems. Three take advantage of the ability to detect manatees using this technology, while the forth focuses on using side-scan sonar to characterize manatee habitat. The most important application at the moment is the confirmation of manatee presence and determination of group size. The second is the detection of mother-calf pairs, based on the relative size of the manatees detected and the association between them. Third, this technology has been very useful in characterizing limnological features of river and lake bottoms, from identified areas with submergent vegetation, to natural holes and depressed areas, which are often favored by manatees for resting. Finally, side-scan sonar has proven to be very effective in aiding manatee capture teams by locating target animals in dark water rivers and lakes in the extensive wetlands of Tabasco, Mexico.

Like all techniques, the use of side-scan sonar has both advantages and limitations, which should be carefully evaluated when considering its use. In most cases, we feel that this technology augments other efforts such as aerial and visual boat surveys, habitat evaluations, and manatee captures, and should be used in combination with these efforts.

There are a lot of possibilities that are yet unknown regarding the use of sonar in manatee conservation and research efforts. Continued experiments with side-scan sonar will determine if this technology can be used as a survey methodology to estimate manatee abundance and density. Other sonars, such as DIDSON, may prove to be useful for examining manatee behavior. In the end, as the technology continues to advance rapidly, we are only limited by our willingness to save these threatened aquatic mammals.

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CONFLICT OF INTEREST

None declared.

APPENDIX

Supplementary descriptive data on side-scan sonar (SSS) images used in this study. Screen captures are from the following locations (noted by the corresponding acronyms): Wetlands of Tabasco, Mexico (WTM); Tortuguero National Park, Costa Rica (TNP); Wetlands of San San Pond Sak, Bocas del Toro, Panama (SSPS). Measurements are presented in their original format without conversion to

Image	Location	Date	Time	Depth	Speed	SSS range	SSS frequency
Fig. 4A	WTM	05/27/2008	1120	16.7 ft		50 ft	262 kHz
Fig. 4B	WTM	02/18/2010	1419	9.6 ft	5.8 mph	45 ft	262 kHz
Fig. 4C1	WTM	02/20/2008	1330	10.6 ft		15 ft	262 kHz
Fig. 4C2	WTM	02/20/2008	1328	9.0 ft		20 ft	262 kHz
Fig. 4C3	WTM	02/20/2008	1327	10.4 ft		30 ft	262 kHz
Fig. 4C4	WTM	02/20/2008	1325	8.8 ft		45 ft	262 kHz
Fig. 4C5	WTM	02/20/2008	1336	8.1 ft		50 ft	262 kHz
Fig. 4C6	WTM	02/21/2008	0811	7.8 ft		60 ft	262 kHz
Fig. 7A	WTM	02/21/2008	1404	7.7 ft		45 ft	262 kHz
Fig. 7B	WTM	05/30/2008	0657	5.4 ft		45 ft	262 kHz
Fig. 7C	WTM	03/23/2006	0820	5.0 ft	3.0 mph	40 ft	262 kHz
Fig. 7D	WTM	05/30/2008	0651	5.7 ft		45 ft	262 kHz
Fig. 8A	WTM	03/22/2006	0935	2.0 ft	4.5 mph	40 ft	262 kHz
Fig. 8B	WTM	02/21/2007	1053	6.7 ft		50 ft	262 kHz
Fig. 8C	TNP	04/08/2010	0949	25.0 ft	4.4 mph	99 ft	455 kHz
Fig. 8D	SSPS	04/20/2007	1923	12.1 ft	8.0 mph	60 ft	455 kHz
Fig. 8E	TNP	04/17/2007	1842	10.9 ft	5.1 mph	30 ft	455 kHz
Fig. 8F	TNP	04/08/2010	1002	19.0 ft	4.9 mph	70 ft	455 kHz
Fig. 9A	WTM	03/23/2006	0808	5.0 ft	2.2 mph	40 ft	262 kHz
Fig. 9B	WTM	07/04/2006	0833	7.0 ft	4.2 mph	40 ft	262 kHz
Fig. 9C	SSPS	04/20/2007	1012	8.8 ft	3.2 mph	40 ft	455 kHz
Fig. 9D	WTM	07/04/2006	0809	7.0 ft	4.6 mph	20ft	262 kHz
Fig. 10A	WTM	02/23/2008	1038	7.4 ft		60 ft	262 kHz
Fig. 10B	WTM	02/23/2008	1043	7.1 ft		60 ft	262 kHz
Fig. 10C	WTM	04/26/2008	1200	4.5 ft		48 ft	262 kHz

metric. Time of day is given in military time (local time) and date as mm/dd/yyyy.

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