Tracking Large Marine Predators in Three Dimensions: The Real-Time Acoustic Tracking System

Mark F. Baumgartner, Lee Freitag, *Member, IEEE*, Jim Partan, Keenan R. Ball, and Kenneth E. Prada

***Abstract*—Large marine predators like sharks and whales can have a substantial influence on oceanic ecosystems, and characterizing their interactions with the physical and biological environment is an important goal in marine ecology. Studies of foraging ecology are of particular importance, but sampling prey aggregations encountered by these predators is extremely difficult because of the small spatial scales over which prey aggregations often occur (meters to hundreds of meters). We developed the real-time acoustic tracking system (RATS) to allow large marine predators to be accurately tracked over these small spatial scales to facilitate proximate environmental sampling. The system consists of an array of four free-floating buoys capable of detecting 36-kHz pings emitted by an animal-borne acoustic transmitter. Upon detection, the buoys transmit their position and the arrival time of the ping via a radio modem to a computer on board a nearby ship, and a software program uses differences in arrival times from all of the buoys to estimate the location of the tagged animal. The positions of the tagged animal, buoys, ship, and support boats can be monitored via a graphical user interface to allow proximate environmental sampling and maintenance of the array around the tagged animal. *In situ* tests indicate that average positional accuracies for a transmitter inside either a four- or three-buoy array (buoys spaced 1–1.75 km apart) are less than 10 m, and that accuracies remain near 10 m for transmitters located up to 500 m away from the edge of the array. The buoys can consistently detect the transmitter up to 1000 m away, but detection rates decrease between 1000 and 2000 m; no detections were obtained beyond 2300 m. Field deployments of the system have demonstrated an unprecedented ability to monitor the movements of baleen whales in real time, allowing a suite of prey and oceanographic observations to be collected within meters to tens of meters of a tagged animal.**

***Index Terms*—Ecology, localization, tags, tracking, whale.**

Manuscript received December 21, 2006; revised October 3, 2007; accepted October 31, 2007. First published September 12, 2008; current version published October 31, 2008. The development of the real-time acoustic tracking system (RATS) was supported by the Cecil H. and Ida M. Green Technology Innovation Fund at the Woods Hole Oceanographic Institution and the National Fish and Wildlife Foundation. The work of M. F. Baumgartner was supported by a Woods Hole Oceanographic Institution Ocean Life Institute Postdoctoral Scholarship. The work of L. Freitag was supported by the Woods Hole Oceanographic Institution W. M. Marquet Award. Collection of field data was supported by a grant from the National Oceanic and Atmospheric Administration Office of Ocean Exploration, and all tagging was conducted under research permit #775-1600-10 issued to the National Oceanic and Atmospheric Administration Northeast Fisheries Science Center.

Associate Editor: J. R. Buck.

M. F. Baumgartner is with the Biology Department, Woods Hole Oceanographic Institution, Woods Hole, MA 02543 USA (e-mail: mbaumgartner@whoi.edu).

L. Freitag, J. Partan, and K. R. Ball are with the Applied Ocean Physics and Engineering Department, Woods Hole Oceanographic Institution, Woods Hole, MA 02543 USA (e-mail: lfreitag@whoi.edu; jpartan@whoi.edu; kball@whoi.edu).

K. E. Prada is with the Upper Cape Systems, East Falmouth, MA 02536 USA (e-mail: kegp@comcast.net).

Digital Object Identifier 10.1109/JOE.2007.912496

I. Introduction

Unlike that of some large terrestrial predators, the foraging behavior of marine predators is difficult to observe because it nearly always occurs out of view below the sea surface. In lieu of visual observations, researchers have embraced tagging technology to observe underwater behavior [1]–[11]. Advances in instrument miniaturization have fostered the development of archival tags that can be attached to animals to record dive characteristics and environmental parameters [12]–[14]. Over the past two decades, these tags have revealed a wide variety of behaviors presumably associated with feeding, yet few studies have attempted to simultaneously measure diving behavior, prey abundance, and local oceanographic conditions to definitively characterize foraging ecology [15], [8]. Today's tags are incapable of assessing prey abundance, and they collect only the most basic oceanographic data (e.g., temperature and, only recently, conductivity). It is unrealistic to expect tags alone to make all of the relevant measurements to characterize foraging behavior because of restrictions on size, weight, and power.

To overcome these limitations of the tags, researchers can take advantage of existing state-of-the-art instrumentation that can be deployed from ships to collect environmental data near marine predators [15], [8]. But how close does one need to be to the predator to adequately characterize the feeding conditions encountered by that predator? Schools of fish or aggregations of zooplankton only meters to hundreds of meters in size can be effectively exploited by marine predators, yet are extremely difficult for researchers to locate and sample. Continuous accurate predator tracking can greatly facilitate studies of feeding conditions by allowing adaptive sampling within meters to tens of meters of the predator using sonar or profiling instruments (e.g., conductivity–temperature–depth profilers, optical plankton counter, video plankton recorder). As in terrestrial studies, tracking marine predators has typically relied on animal-borne radio transmitters [16]–[18], but these only provide a signal when an animal is at the surface. Radio tracking is impossible for fish that do not come to the surface at all, and the low accuracy and coarse resolution of the resulting positions for radio-tagged marine mammals hinders sampling that is close enough to the predator in space (meters to tens of meters) and time (seconds to minutes) to adequately characterize a patchy feeding environment.

This paper describes a system designed to accurately track marine predators continuously while they are submerged. The system, called the real-time acoustic tracking system (RATS), is based on the detection and localization of acoustic transmissions emitted from an animal-borne tag by a free-floating moveable array of buoys. The concept of operation is similar to other wide-aperture hydrophone arrays [19], [20], but the RATS provides location estimates in real time and does not depend on the target animal to produce sound for tracking. Our initial goal in developing the RATS was to monitor the foraging behavior of baleen whales. Baleen whales spend the majority of their time submerged; therefore, tracking by radio telemetry alone for proximate prey and oceanographic sampling is difficult and inaccurate. Baleen whales are ideally suited for tracking by a free-floating array, since they can be approached and tagged at close range, many tend to remain in a confined area while actively foraging [8], and they are relatively slow moving. We originally specified the RATS to have a positional accuracy of less than 20 m, which corresponds roughly to a single body length of a baleen whale.

II. System Description

A. Acoustic Transmitter

The RATS tracks an acoustic transmitter that is attached to a marine animal. Tag attachment methods vary between species; for attachments to whales, suction-cup mounted tags are common [2], [6]–[10], [18]. We developed the RATS to track the model V22P acoustic transmitter manufactured by Vemco, Ltd. (Halifax, NS, Canada), which is specified to transmit a 36-kHz "ping" at 165 dB (re 1 μP @ 1 m) once every 700–1100 ms. The pulse duration of the ping is 10 ms. The V22P carries an integrated pressure transducer, and the interval between pings is varied linearly with the pressure measurement. Thus, the depth of the transmitter (Z) can be determined remotely by measuring the interval between received pings (Δt) and applying a factory-supplied linear calibration equation as follows:

$$Z = \lambda + \kappa(\Delta t) \tag{1}$$

where λ and κ are the intercept and the slope of the linear calibration equation, respectively.

Since we initially designed the RATS to monitor the foraging behavior of baleen whales, it was critical that the acoustic transmitter not interfere with the tagged animal's behavior by being bothersome. Ideally, the transmitter will be inaudible, and this is accomplished by choosing a frequency that is above the hearing range of the target species. However, attenuation of the acoustic signal increases exponentially with the frequency; therefore, choosing too high a frequency can dramatically reduce the detection range. We chose a 36-kHz transmitter because the available evidence indicates that many baleen whales cannot hear sounds above roughly 25 kHz. The hearing range for mammalian ears can be estimated by measuring the thickness-to-width ratios of the basilar membrane in the cochlea [21]. Houser *et al.* [22] and Parks [23] used this method to estimate that the upper hearing limit of humpback whales is 18 kHz and that of right whales is 22 kHz, respectively. Ketten [24] reports similar thickness-to-width ratios at the base of the basilar membrane for humans and right, humpback, and fin whales, suggesting that they all have similar high-frequency hearing limits (~20 kHz). The 36-kHz V22P transmitter emits a ping that is nearly one octave above this limit and is inaudible to humans; field observations suggest it is inaudible to right, humpback, and fin whales as well. Baumgartner and Mate [8] used a 36-kHz V22P transmitter in a portion of their right whale foraging ecology study, and they found no differences in the diving behavior of whales tagged with and without the transmitters. Moreover, Watkins [25] summarized nearly 30 years of observing whales exposed to sounds and concluded that "higher frequency sounds generated by our pingers and sonars at 36, 40, 50, 60 kHz and higher were apparently not noticed, even at close range by finbacks, humpbacks, and right whales, as long as the signals contained little energy in the lower-frequency pulse-envelopes." Frankel [26] reported that gray whales responded to a 21–25-kHz sonar, suggesting that gray whale hearing is perhaps more sensitive than other baleen whales at higher frequencies; however, the source levels used by Frankel [26] were quite high (215 dB re 1 μPa at 1 m). Our tests of the V22P transmitter indicate that it emits no energy below 30 kHz (Fig. 1), and we therefore believe it is inaudible to our target taxa.

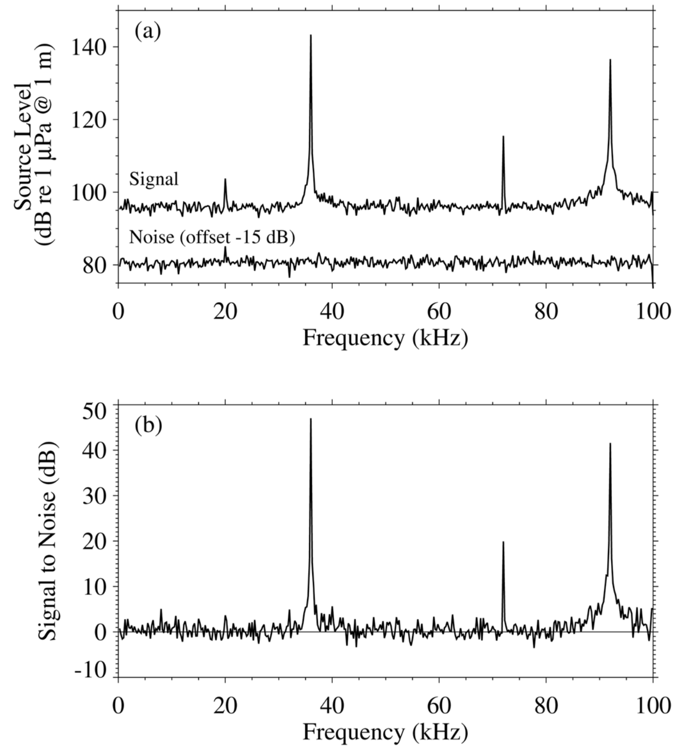

Fig. 1. (a) Average source level spectra from open-water recordings of three Vemco V22P transmitters using a Reson TC4033 hydrophone placed 1 m away from the transmitter. Noise spectrum was derived from the period of silence between pings, and it is shown with a −15-dB offset for clarity. (b) Signal-to-noise ratio. The transmitters are designed to transmit at 36 kHz, but energy is also present at 72 (harmonic) and 92 kHz. The small peak at 20 kHz measured in (a) was not produced by the transmitters (note its presence in the noise spectrum); it was a background continuous tone from an unidentified source at the test site in Woods Hole harbor, MA.

B. Buoys

The function of a RATS buoy is to detect pings emitted by the animal-borne acoustic transmitter and upon detection, to immediately relay to the ship: 1) the position of the buoy and 2) the exact time the ping was detected. In the absence of detections, a RATS buoy relays only its position to the ship once every 2 s. The system consists of four RATS buoys, and tracking can be accomplished when either three or four of the buoys are deployed.

1) Hardware: The buoys were designed to be compact and hand-deployable. They consist of an instrument well surrounded by Surlyn foam flotation, a hydrophone suspended 3.6 m below the instrument well, and a mast carrying a radio antenna and a global positioning system (GPS) receiver [Fig. 2(a)]. A bail on the instrument well provides a means to easily deploy or recover the buoy either by hand or with a gaff. The faceplate of the instrument well has a rotary switch to turn the buoy on and off, and several watertight connectors to accommodate cables from the hydrophone, radio antenna, and GPS. The mast is constructed from Extren tubing inside which the radio antenna is mounted for protection. The GPS receiver is attached to the exterior of the mast so that it has an unobstructed view of the sky. The hydrophone is suspended from the instrument well with a load-bearing conducting cable. To keep the cable in a vertical orientation and to help stabilize the buoy, a custom-molded 6.8-kg lead weight is attached to the load-bearing cable. The cable passes through this weight and connects to the hydrophone, which protrudes from the bottom of the weight into a protective stainless steel cage [Fig. 2(a)].

2) Electronic Components: The chassis inside the instrument well holds an acoustic receiver, radio modem, and a battery [Fig. 2(b)]. The hydrophone and GPS are connected to the acoustic receiver, and the radio antenna is connected to the radio modem. We used a High Tech, Inc. (Gulfport, MS) model HTI-96-MIN voltage mode hydrophone with an internal preamplifier that provided a sensitivity of -165 dB re 1 V/μPa. The acoustic receiver is a Woods Hole Oceanographic Institution (WHOI, Woods Hole, MA) micromodem [27] with custom firmware designed to detect 36-kHz pings using a matched filter. The hydrophone is sampled by the micromodem at 80 kHz, and the resulting signal is demodulated at 36 kHz and decimated to 8 kHz before application of the matched filter.

The GPS (Garmin, Olathe, KS, model GPS16 HVS) outputs a 1 pulse/s (PPS) signal (± 1-μs accuracy) that is used by the acoustic receiver as a stable and accurate clock. The GPS also reports time and position to the acoustic receiver at 1 Hz via a serial RS232 interface. An internal 80-kHz counter measures the time elapsed since receipt of the last PPS signal [28]; therefore, all detection events can be accurately referenced in time. Because the PPS signal is synchronized across all GPS receivers, the buoys operate on the same time base. Thus, differences in detection times between buoys can be accurately measured. Positions from the GPS are of the highest quality available for the deployment area. In the offshore waters of North America where the wide area augmentation system (WAAS) is available, position accuracy is less than 3 m.

Upon detection of a 36-kHz ping, the acoustic receiver relays to the radio modem (Freewave, Boulder, CO, FGR-series 900-MHz spread spectrum wireless radio) a data sentence containing the buoy's identification number, the time of the detection (reported to hundreds of microseconds), the position of the buoy, and diagnostic information. The radio modem then transmits this data sentence to the ship (Fig. 3). If no detection events occur within 2 s, the system transmits to the ship a data sentence containing the buoy's identification number, the current time, and the buoy's position. All electronic components are powered from a single 12-V, lead-acid, rechargeable battery.

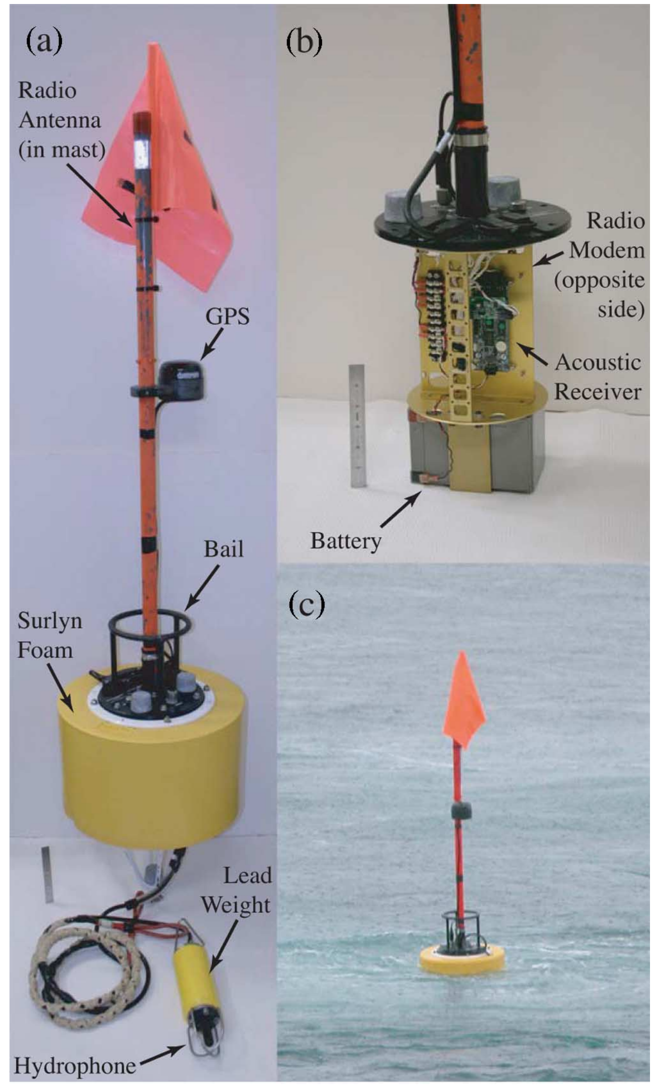

Fig. 2. Photographs of (a) RATS buoy, (b) interior chassis, and (c) deployed RATS buoy. A 15-cm ruler is shown in (a) and (b) for scale.

C. Other Hardware

1) Boat Boxes: To facilitate operations in the field, we developed a capability to track small boats tasked with moving the buoy array. The boats each carry a "boat box," which consists of a GPS, Freewave radio modem, radio antenna, battery, and battery charger (Fig. 3). The radio modem, battery, and battery charger are housed in a watertight enclosure, and the radio antenna and GPS are mounted on an attached mast that is identical to the mast used on the buoys. The GPS continuously outputs time and position at 1 Hz, and these data are transmitted immediately to the ship via the radio modem.

2) Master: A single enclosure called the "master" is used on the ship: 1) to receive radio-telemetered data from the buoys and boat boxes and to relay these data to a computer via a RS232

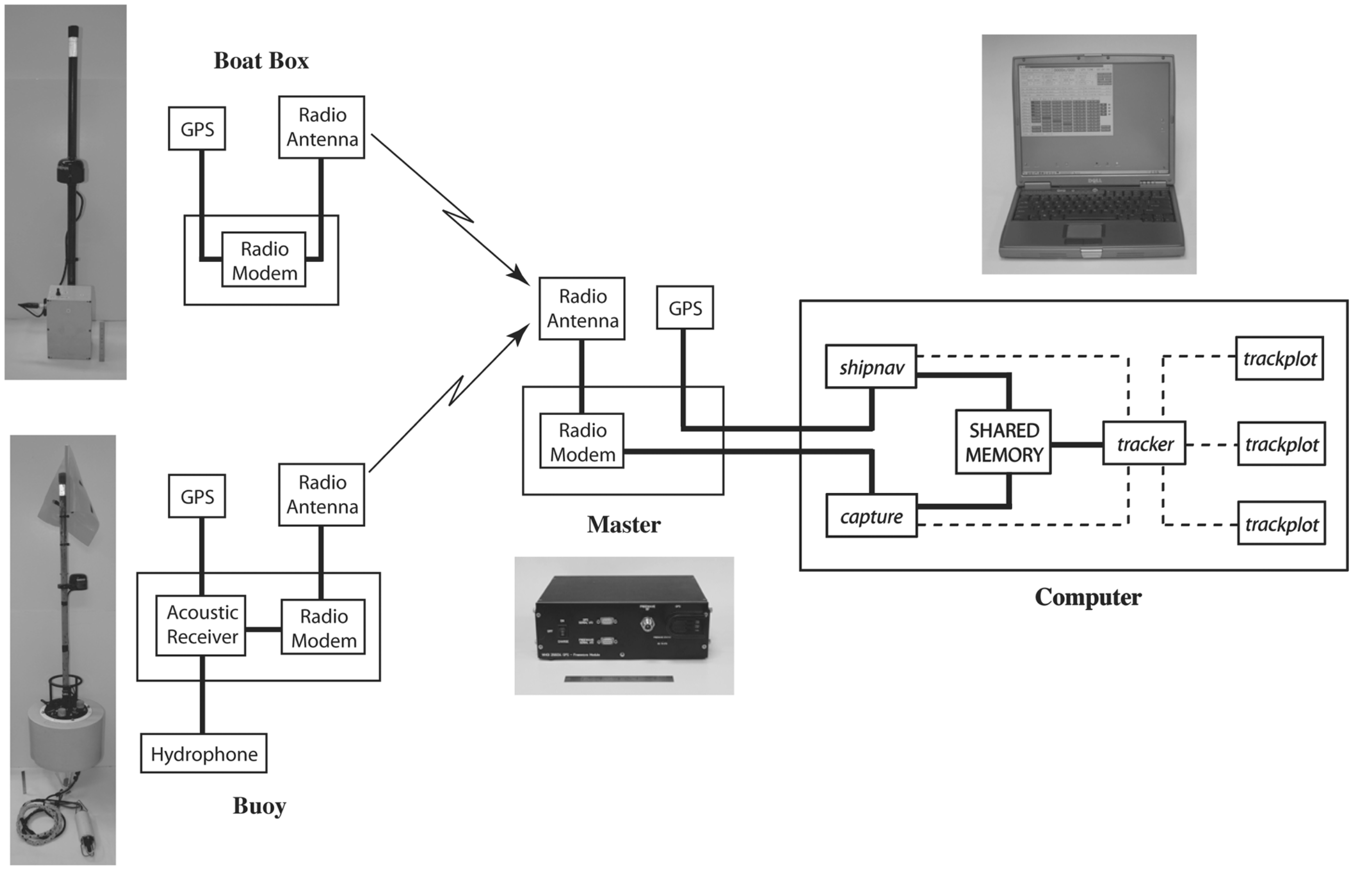

Fig. 3. Diagram of RATS components and communication pathways. Computer programs are shown in italics and interprocess communications are indicated by dashed lines. A 15-cm ruler is shown in the photographs of the boat box, buoy, and master for scale.

port, and 2) to acquire time and ship's position from an attached GPS and relay it to the same computer via a second RS232 port. The master houses a Freewave radio modem, a battery, and a battery charger (Fig. 3), and it has input ports to accommodate cables from a radio antenna and a GPS that are both mounted on a short pole. This pole can be easily attached to the ship's mast or some other fixed structure that has an unobstructed view of the sky. The master's radio modem receives data sentences from all of the buoys and boat boxes via the antenna and relays them to the computer through one of the RS232 serial ports. Continuous output from the GPS receiver is passed to the other RS232 serial port at 1 Hz. Both the radio modem and the GPS are powered from the rechargeable lead-acid battery housed inside the master.

D. Software

The RATS computer software was developed for the Linux operating system because it has a reliable threaded kernel, supports interprocess communication (IPC) and shared memory, and is available for low-cost personal computers. For portability, we designed the software to be run on a Dell (Round Rock, TX) Inspiron laptop computer (model 600m) with an attached 17-in external monitor. The laptop has a single integrated RS232 serial port that is dedicated to receiving the radio modem input from the master. We used a USB-RS232 adapter to allow input of the ship's GPS data from the master through the laptop's integrated universal serial bus (USB) port. The software system uses independent programs to carry out specific tasks. Data is passed back and forth between these programs using shared memory, and the programs communicate with one another using IPC signals.

1) Data Sentence Processing: The RATS software processes data sentences from the master using two separate programs: *shipnav* and *capture* (Fig. 3). The program *shipnav* ingests and processes sentences from the ship's GPS, whereas *capture* handles sentences originated by the buoys or the boat boxes and transmitted via the radio modem. All sentences, regardless of their source, have an appended checksum. Both *shipnav* and *capture* verify the integrity of received sentences using this checksum, and then write conforming sentences to separate archival files. Data sentences are parsed and the resulting data are written to the appropriate variables in shared memory for access by other programs. Both *shipnav* and *capture* signal the display program *tracker*, when new data is available in shared memory for display. If *capture* receives a buoy sentence that contains a valid acoustic detection, it will also attempt to localize the acoustic transmitter using the algorithm described in Section II-D3.

2) Display: The RATS display system is controlled by the graphical user interface (GUI) program *tracker* (Fig. 4), which allows the user to: 1) monitor the movements of the tagged animal in real time; 2) monitor the configuration of the buoy array; 3) monitor the position of the ship and small boats; 4) monitor the performance of the localization algorithm;

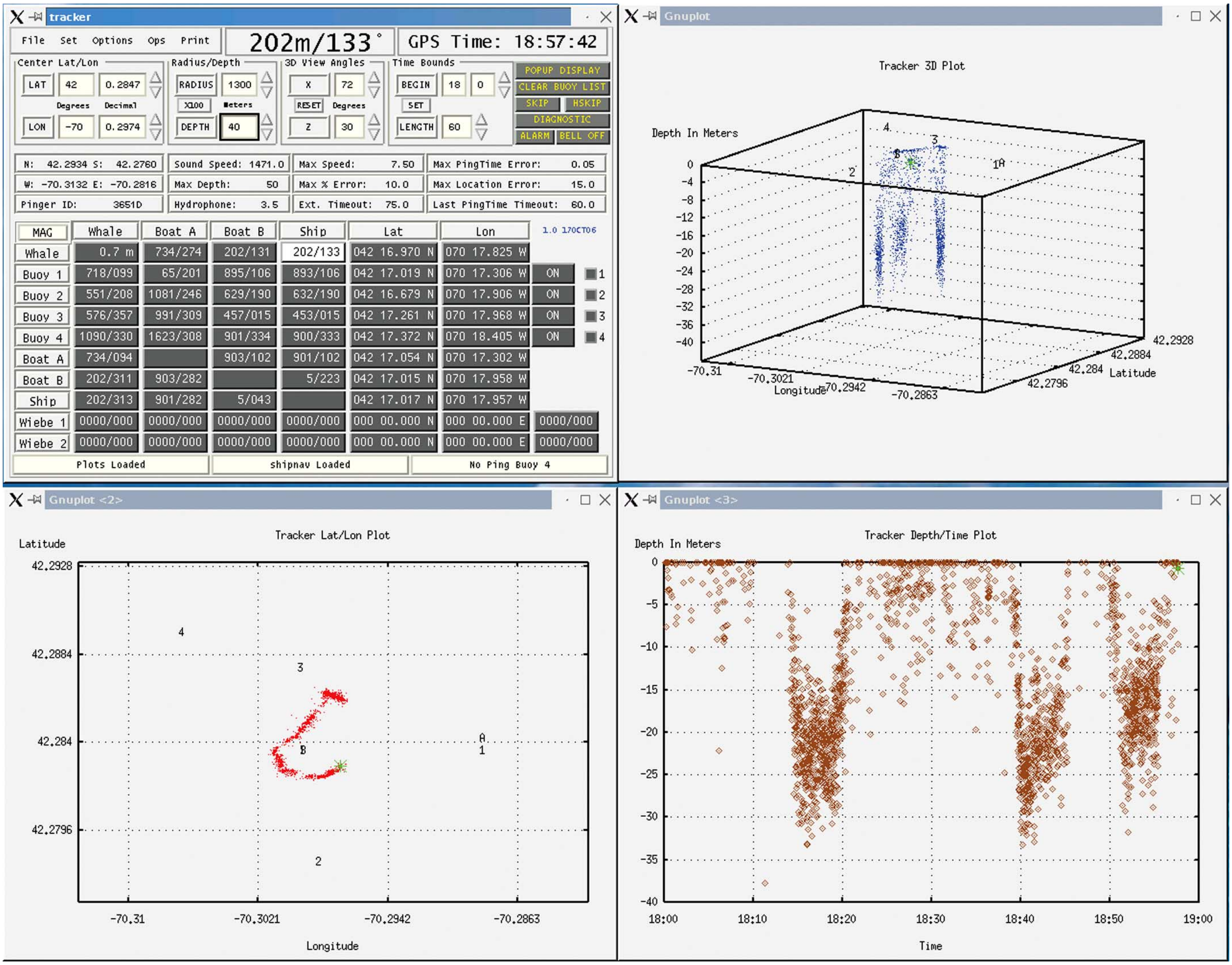

Fig. 4. Tracking software GUI, including main window controlled by *tracker* (upper left) and three display windows controlled by separate instances of *trackplot* showing a plan view (lower left), time-depth plot (lower right), and 3-D view (upper right). Buoy positions (numbers), boats (letters "A" and "B"), and ship (letter "S") are shown on plan and 3-D plots (boat box B was carried aboard the ship, so the ship is shown as a superimposed "B" and "S"). The whale's position is shown as a green asterisk in all of the plots. The real-time display shown here is for the same data depicted in Fig. 9.

5) change localization processing parameters; and 6) change display parameters. The bulk of the *tracker* display is devoted to a data table that reports the distance and the bearing from the ship and the small boats to all of the other objects (e.g., tagged animal, buoys, small boats). This display allows the ship and the small boats to maneuver in proximity to the tagged animal to conduct proximate sampling and to easily retrieve and reposition the buoys.

In addition to the primary GUI, three instances of the program *trackplot* each display a different visualization of the position and depth data as they evolve in time: 1) a plan view, 2) a 3-D plot of position and depth, and 3) a depth versus time plot (Fig. 4). The *trackplot* program is actually the widely available, open source program *gnuplot* (copyright T. Williams and C. Kelley) modified to update a plot upon receipt of an IPC signal. When update requests are sent to *tracker* by *shipnav* or *capture*, *tracker* writes separate, text-based, plot command files and then sends a signal to each of the three instances of *trackplot*. Upon receipt of these signals, *trackplot* reads the plot command files and redraws the display window.

3) Localization: The RATS software localizes the acoustic transmitter on the tagged animal with detections from either three or four buoys using equations adapted from Watkins and Schevill [29]. The localization algorithm assumes that a ping detected by the RATS buoys traveled in a straight path from the transmitter to the buoy hydrophones (i.e., there is no ray bending, shadowing, or reflection off the sea surface or seafloor). Thus, the distance between each hydrophone and the transmitter is equal to the product of the speed of sound and the travel time between the transmitter and the hydrophone

$$(X - x_i)^2 + (Y - y_i)^2 + (Z - z_i)^2 = c^2 T_i^2 \qquad (2)$$

where x_i, y_i, and z_i describe the location of the hydrophone on buoy i, T_i is the time between the emission of a ping by the transmitter and the reception of that ping at the hydrophone on buoy i, c is the speed of sound, and X, Y, and Z describe the position of the transmitter. To solve this set of equations [29], all positions and times are expressed relative to buoy 1 ($\hat{x}_i = x_i - x_1, \hat{y}_i = y_i - y_1, \hat{z}_i = z_i - z_1, \hat{X} = X - x_1, \hat{Y} = Y - y_1, \hat{Z} = Z - z_1, \tau_i = T_i - T_1$) so that $\hat{x}_1 = \hat{y}_1 = \hat{z}_1 = \tau_1 = 0$. The system expressed in (2) then becomes

$$\hat{X}^2 + \hat{Y}^2 + \hat{Z}^2 = c^2 T_1^2 \tag{3}$$

for $i = 1$ and

$$(\hat{X} - \hat{x}_i)^2 + (\hat{Y} - \hat{y}_i)^2 + (\hat{Z} - \hat{z}_i)^2 = c^2(\tau_i + T_1)^2 \tag{4}$$

for $i > 1$. To solve for $\hat{X}, \hat{Y}$, and T_1 [recall that Z, the depth of the transmitter, is derived independently from the ping interval using (1)], (3) is subtracted from the system described in (4). This gives

$$\hat{x}_i \hat{X} + \hat{y}_i \hat{Y} + c^2 \tau_i T_1 = \frac{1}{2}\left(R_i - c^2\tau_i^2\right) - \hat{z}_i \hat{Z} \tag{5}$$

where $R_i = \hat{x}_i^2 + \hat{y}_i^2 + \hat{z}_i^2$. For brevity in (9)–(14), we define the following:

$$\omega_i = \frac{1}{2}\left(R_i - c^2\tau_i^2\right) - \hat{z}_i \hat{Z} \tag{6}$$

$$\alpha = \frac{c^2(\hat{x}_2\tau_3 - \hat{x}_3\tau_2)}{\hat{x}_2\hat{y}_3 - \hat{x}_3\hat{y}_2} \tag{7}$$

$$\beta = \frac{\hat{x}_2\omega_3 - \hat{x}_3\omega_2}{\hat{x}_2\hat{y}_3 - \hat{x}_3\hat{y}_2}. \tag{8}$$

When all four buoys are in the water ($i = 1, 2, 3, 4$), the system in (5) consists of three equations and three unknowns. The solution to this system is as follows:

$$T_1 = \frac{\hat{x}_2\omega_4 - \hat{x}_4\omega_2 - \beta(\hat{x}_2\hat{y}_4 - \hat{x}_4\hat{y}_2)}{c^2(\hat{x}_2\tau_4 - \hat{x}_4\tau_2) - \alpha(\hat{x}_2\hat{y}_4 - \hat{x}_4\hat{y}_2)} \tag{9}$$

$$\hat{X} = \frac{\omega_2 - \beta\hat{y}_2 + (\alpha\hat{y}_2 - c^2\tau_2)T_1}{\hat{x}_2} \tag{10}$$

$$\hat{Y} = \beta - \alpha T_1. \tag{11}$$

When only three buoys are in the water ($i = 1, 2, 3$), the system in (5) consists of two equations and three unknowns (however, a solution to this system can be determined because T_1 is dependent upon X, Y, and Z). To solve this system [29], first express $\hat{X}$ and $\hat{Y}$ as linear functions of T_1

$$\hat{X} = U_{\hat{X}} T_1 + V_{\hat{X}} \tag{12}$$

$$\hat{Y} = U_{\hat{Y}} T_1 + V_{\hat{Y}} \tag{13}$$

where $U_{\hat{X}} = (\alpha\hat{y}_2 - c^2\tau_2)/(\hat{x}_2), V_{\hat{X}} = (\omega_2 - \beta\hat{y}_2)/(\hat{x}_2), U_{\hat{Y}} = -\alpha$, and $V_{\hat{Y}} = \beta$. Equations (12) and (13) are substituted in (3) and T_1 is solved using the quadratic equation

$$T_1 = \frac{-b \pm \sqrt{b^2 - 4ad}}{2a} \tag{14}$$

where $a = U_{\hat{X}}^2 + U_{\hat{Y}}^2 - c^2, b = 2(U_{\hat{X}}V_{\hat{X}} + U_{\hat{Y}}V_{\hat{Y}})$, and $d = V_{\hat{X}}^2 + V_{\hat{Y}}^2 + \hat{Z}^2$. The quadratic equation provides two solutions for T_1. In cases where the transmitter is inside a well-configured array, one solution for T_1 will be positive and one will be negative. Only the positive solution is plausible (i.e., it is impossible for a hydrophone to detect a ping prior to the transmitter emitting that ping).

Measurement errors in the time-of-arrival differences (τ_i) can introduce error in the linear solutions above, and these errors will change with the configuration of the array (e.g., larger errors will occur when the buoys are equidistant from the transmitter). Because there is redundancy in the four-buoy solution, we used an iterative refinement procedure to reduce these errors [30], [31]. We can express the measurement errors (e_i) as

$$e_i = m_i - f_i \tag{15}$$

where $m_i = c\tau_i$ is the measured quantity and $f_i = \sqrt{(X - x_i)^2 + (Y - y_i)^2 + (Z - z_i)^2} - cT_1$ is the corresponding true value if X, Y, and T_1 represent the true position (X, Y) and the travel time to buoy 1 (T_1). Our goal is to iteratively refine an initial estimate of X, Y, and T_1 given the observed time-of-arrival differences (τ_i) by minimizing the sum of squared errors. The initial estimate will be the linear solutions derived in (9)–(11). We can then express f_i as a first-order Taylor series expansion about these initial estimates of X, Y, and T_1

$$f_i \cong f_i(X, Y, T_1) + \frac{\partial f_i}{\partial X}\delta_X + \frac{\partial f_i}{\partial Y}\delta_Y + \frac{\partial f_i}{\partial T_1}\delta_{T_1}. \tag{16}$$

Then

$$\frac{\partial f_i}{\partial X}\delta_X + \frac{\partial f_i}{\partial Y}\delta_Y + \frac{\partial f_i}{\partial T_1}\delta_{T_1} = c\tau_i - r_i + cT_1 - e_i \tag{17}$$

can be represented in matrix notation as

$$A\delta \cong B - e \tag{18}$$

where

$$A = \begin{bmatrix} \frac{X - x_1}{r_1} & \frac{Y - y_1}{r_1} & -c \\ \frac{X - x_2}{r_2} & \frac{Y - y_2}{r_2} & -c \\ \frac{X - x_3}{r_3} & \frac{Y - y_3}{r_3} & -c \\ \frac{X - x_4}{r_4} & \frac{Y - y_4}{r_4} & -c \end{bmatrix}$$

$$\delta = \begin{bmatrix} \delta_X \\ \delta_Y \\ \delta_{T_1} \end{bmatrix}$$

$$B = \begin{bmatrix} c\tau_1 - r_1 + cT_1 \\ c\tau_2 - r_2 + cT_1 \\ c\tau_3 - r_3 + cT_1 \\ c\tau_4 - r_4 + cT_1 \end{bmatrix}$$

$$e = \begin{bmatrix} e_1 \\ e_2 \\ e_3 \\ e_4 \end{bmatrix}$$

and $r_i = \sqrt{(X - x_i)^2 + (Y - y_i)^2 + (Z - z_i)^2}$ when four buoys are in the water (note the columns of A result from differentiating f_i with respect to X, Y, and T_1). If the errors (e_i)

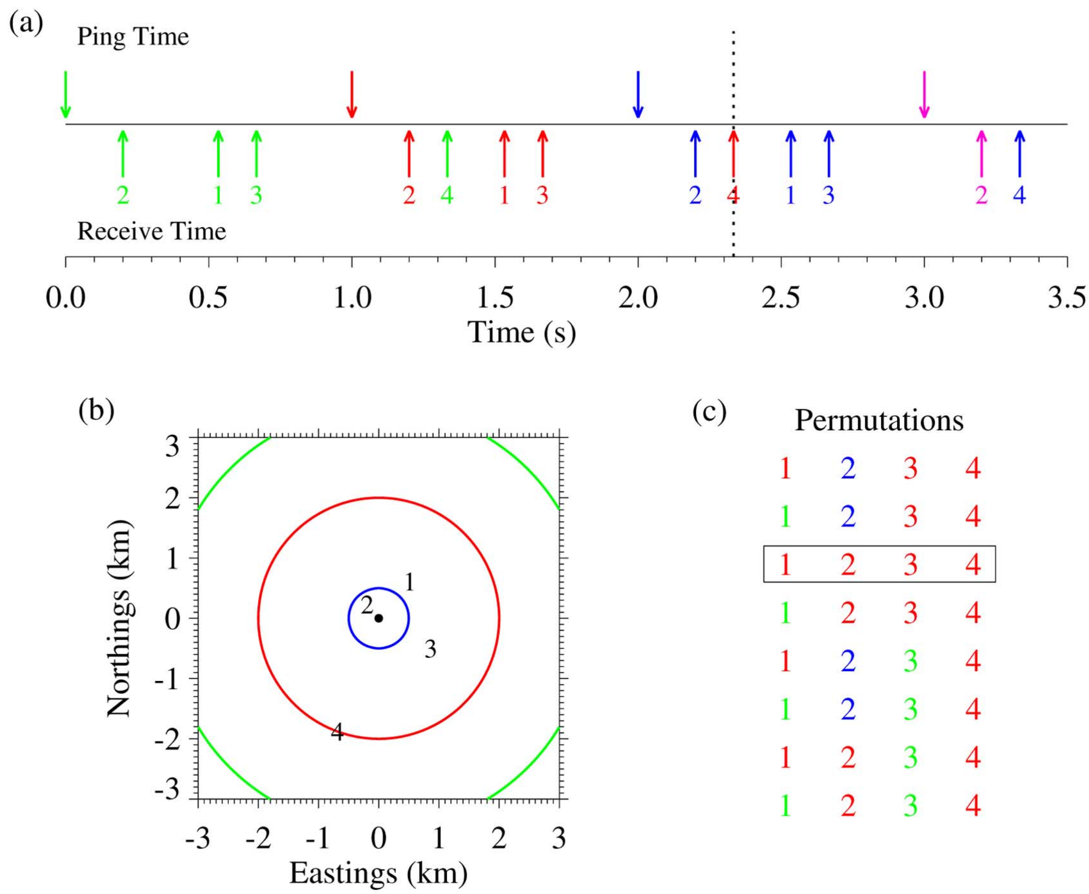

Fig. 5. Example of ping reception timing. (a) Times when a transmitter emits a ping (above line) and when each of the four buoys receives that ping (below line). Pings are individually identified by color. Plots in (b) and (c) correspond to the time indicated by the vertical dotted line in (a). (b) Map indicating the position of the transmitter (filled circle in the center), the position of the buoys (numbers), and where prior pings are currently being detected [concentric circles; colors as in (a)]. (c) Table indicating permutations of recently received pings, only one of which includes receptions of the same ping. Because pings are not actually individually identified as shown here, equations (20)–(22) are required to identify invalid permutations.

are independent with zero means and equal variances, then the solution to (18) is

$$\delta = [A^T A]^{-1} A^T B \tag{19}$$

[30] and the estimates of X, Y, and T_1 are updated as $X = X + \delta_X, Y = Y + \delta_Y$, and $T_1 = T_1 + \delta_{T_1}$. These new estimates of X, Y, and T_1 are used in (18) and the process is repeated until the changes in the position (i.e., $\sqrt{\delta_X^2 + \delta_Y^2}$) are small. Convergence on a stable estimate typically occurs within just a few iterations.

The previously described procedures can accurately estimate the location of the transmitter when each of the buoys receives the same identifiable ping. That is, the localization will be successful if the pings received at the buoys at times T_1, T_2, T_3, and T_4 all originated as a single emission from the transmitter at time T. However, since none of the pings in the RATS are individually identifiable, there is no way to know for certain if a ping received at buoy 1 at T_1 originated as the same ping that is heard at buoy 2 at T_2 (Fig. 5). Because of this uncertainty, the software constructs permutations of all recently received buoy sentences. Only one of the permutations contains detections of the same ping [Fig. 5(c)], and most of the invalid permutations can be detected by comparing the distances between buoys to their accompanying arrival time differences as follows:

$$|T_i - T_j| \leq \frac{D_{ij}}{c} \tag{20}$$

where D_{ij} is the distance between buoy i and buoy j. If this inequality is true for all buoy pairs in a permutation, the software proceeds to estimating the position of the transmitter.

When the transmitter is well positioned inside the buoy array, the procedures described previously typically produce unambiguous results. However, when conditions are less than ideal (e.g., irregularly shaped array, highly stratified conditions, transmitter near the surface where ray bending may occur), more than one seemingly valid localization can be produced. In such cases, external, user-supplied information is required to identify the appropriate solution. The tracking software allows the user to identify a good solution, and once identified, attempts to ignore spurious solutions thereafter. The estimated ping time (t_p, derived from T_1) and transmitter depth (Z) from the good solution are used to predict future ping times as follows:

$$t_{p+k} = t_p + k \left[\frac{Z - \lambda}{\kappa} \right] \tag{21}$$

where λ and κ are from (1) and k is a positive integer. If the estimated ping time for a particular solution is sufficiently close to t_{p+k} for $k > 0$ (within tens of milliseconds), that solution is considered provisionally valid. The solution is then further examined with a simple swimming speed check by comparing the estimated position and time to the last good solution using the following inequality:

$$D < S_{\max} dt + 2e_r \quad (22)$$

where D and dt are the distance and time between the estimated solution and the last good solution, respectively, $S_{\max}$ is a user-specified maximum swimming speed for the tagged animal (ca. 7.5 m $\cdot$ s^{-1} for baleen whales), and e_r is the radial location error for the system (we set $e_r = 15$ m based on the accuracy tests described in Section III). If a solution passes both the ping time (21) and swimming speed (22) tests, the solution is considered valid. For tracking marine mammals, good solutions can be identified by establishing visual contact with the tagged animal at the sea surface. However, in other applications (e.g., tracking fish), this may not be feasible. The best course of action to avoid ambiguous results is to maintain the free-floating buoy array in an optimal configuration around the tagged animal; vigilance is required to achieve this in a highly advective environment or while tracking a very mobile animal.

III. *In Situ* Accuracy Tests

To test both the detection range and the accuracy of the RATS, we deployed the buoys on April 13, 2006 in an area of Cape Cod Bay, MA, with water depths ranging from 12 to 17 m. The buoys were deployed in a roughly square configuration with 1–1.75-km separating buoys along the perimeter of the square (Fig. 6). After buoy deployment, the ship returned to the middle of the array and lowered an acoustic transmitter to 8-m depth. One of the boat boxes was placed on the ship's deck directly above the submerged transmitter to continuously record its exact geolocation. The ship then steamed slowly toward the northeast for 39 min until acoustic detections were no longer received from any of the buoys (Fig. 6). Location errors reported in Section III-B were determined as the horizontal distance between the actual position of the transmitter (derived from the boat box) and the estimated position of the transmitter (derived from the localization procedure). The vertical dimension was ignored for these horizontal error estimates; however, a Wildlife Computers (Redmond, WA) MK9 time–depth recorder was collocated with the acoustic transmitter during the test so that errors in the telemetered depth measurement (1) could be independently evaluated.

A. Detection Range

The RATS buoys detected the transmitter consistently at ranges of up to 1000 m during the test (Fig. 7). Detections declined steadily with distance at ranges of 1000–2000 m, and were reduced to nearly zero beyond 2300 m. We expect that detection distance will vary as a function of transmitter depth and hydrographic conditions; however, these detection range results are consistent with our experience using the RATS in other areas at different times of the year.

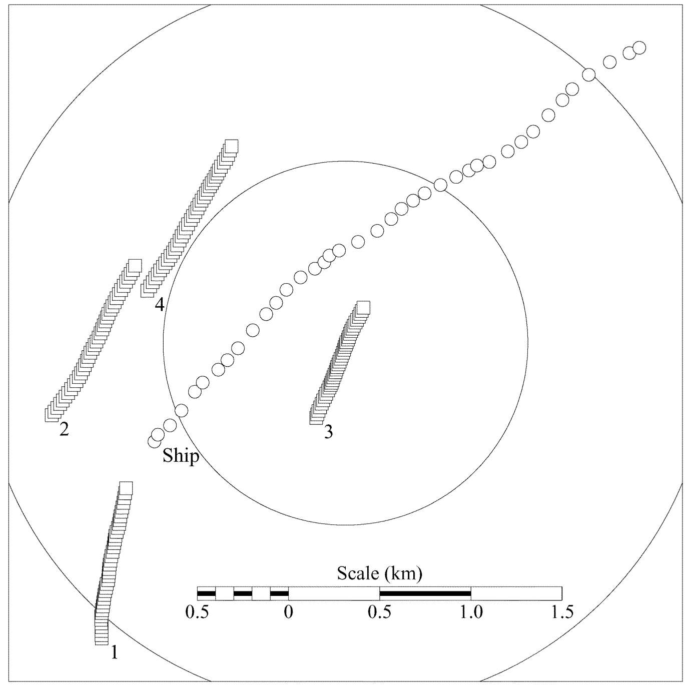

Fig. 6. Ship (circles) and buoy tracks (squares) during 39-min, at-sea, system accuracy test. Ship and buoy labels are near starting positions. Concentric circles are separated by 1 km.

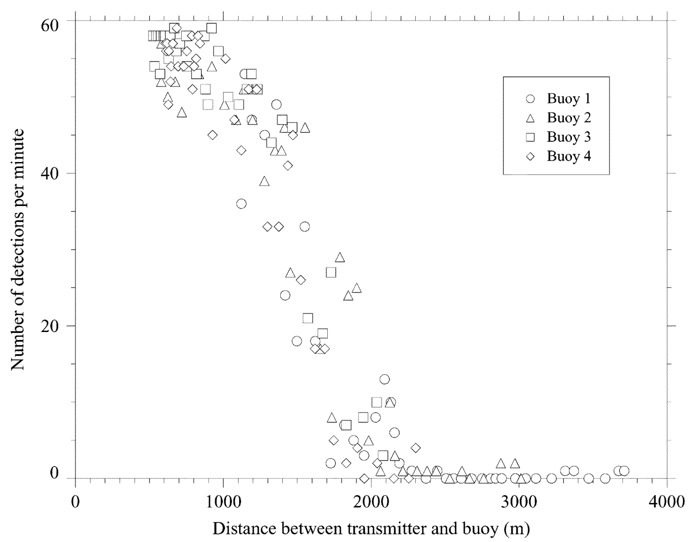

Fig. 7. Number of detections per minute as a function of range from the transmitter. During the test, the transmitter (serial 1689F, $\kappa = -1052.3$ m $\cdot$ s^{-1} and $\lambda = 1092.3$ m) was held at a nominal depth of 8 m and emitted pings at a rate of 58 min^{-1} [the interval between pings was 1.0304 s; see (1)].

B. Accuracy Test

The accuracy of the system was examined as a function of the distance from the buoy array and the number of buoys used to estimate the transmitter location (Fig. 8). While the acoustic transmitter was inside the array, location errors for the four-buoy solutions averaged 7.3 m [$n = 229$, standard deviation (SD)

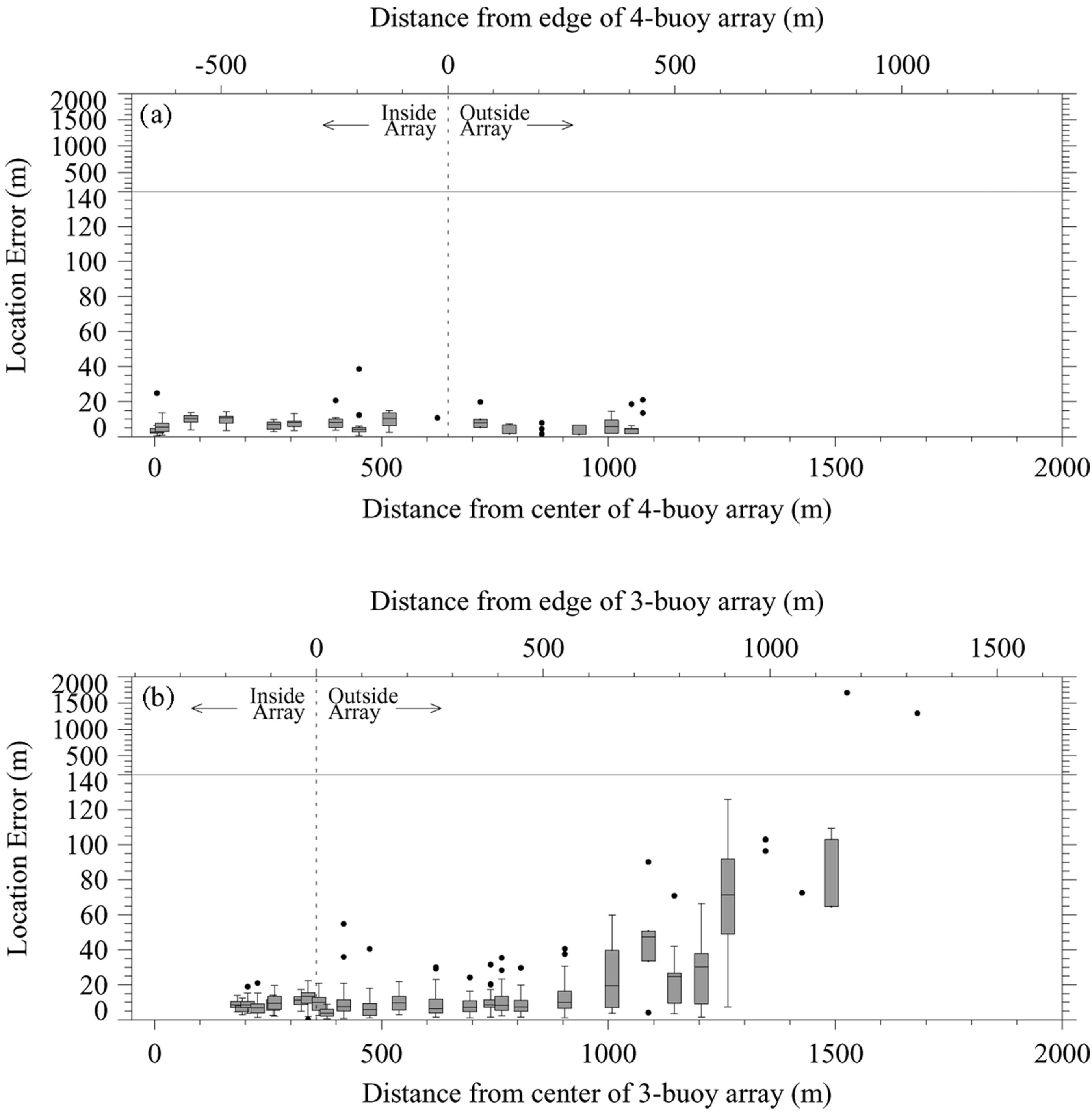

Fig. 8. Location errors as a function of the distance from the (a) four-buoy and (b) three-buoy arrays. Errors are summarized for each 1-min interval during the 39-min test as box and whisker plots showing the median error (middle line), interquartile range (box), errors within 1.5 × the interquartile range (whiskers), and outliers (filled circles). For 1-min periods with fewer than four successful localizations, data are shown as filled circles only. The vertical dotted line depicts the edge of the array. Note a break in the scale of these plots indicated by the horizontal line.

= 4.4 m, root mean square (RMS) error = 8.5 m] and errors for the three-buoy solutions (omitting buoy 1) averaged 9.2 m ($n = 508$, SD = 3.9 m, RMS error = 9.9 m). Position accuracy was expected to degrade with distance outside the array; however, errors for four-buoy solutions while the transmitter was outside the array averaged only 7.0 m ($n = 33$, SD = 5.2 m, RMS error = 8.7 m). Errors for three-buoy solutions outside the array also remained low until the transmitter was moved over 500 m away from the edge of the array [Fig. 8(b)]. The average three-buoy solution error was 8.6 m ($n = 484$, SD = 6.2 m, RMS error = 10.6 m) within 500 m of the edge of the array, and the median errors increased from 10 to 100 m between 500 and 1200 m from the edge of the array. We anticipate that four-buoy solution errors would similarly increase beyond 500 m from the edge of the array, but no solutions could be obtained beyond this point because the range exceeded the detection limit of buoy 1

TABLE I
ERRORS (M) IN DEPTH MEASUREMENTS TELEMETERED BY THE VEMCO V22P ACOUSTIC TRANSMITTER

Buoy	N	Average	SD	RMS
1	259	-0.52	3.35	3.39
2	851	-0.45	3.66	3.69
3	1676	0.06	3.06	3.06
4	1326	-0.02	3.49	3.49
Averaged estimate	1240	0.16	2.29	2.29

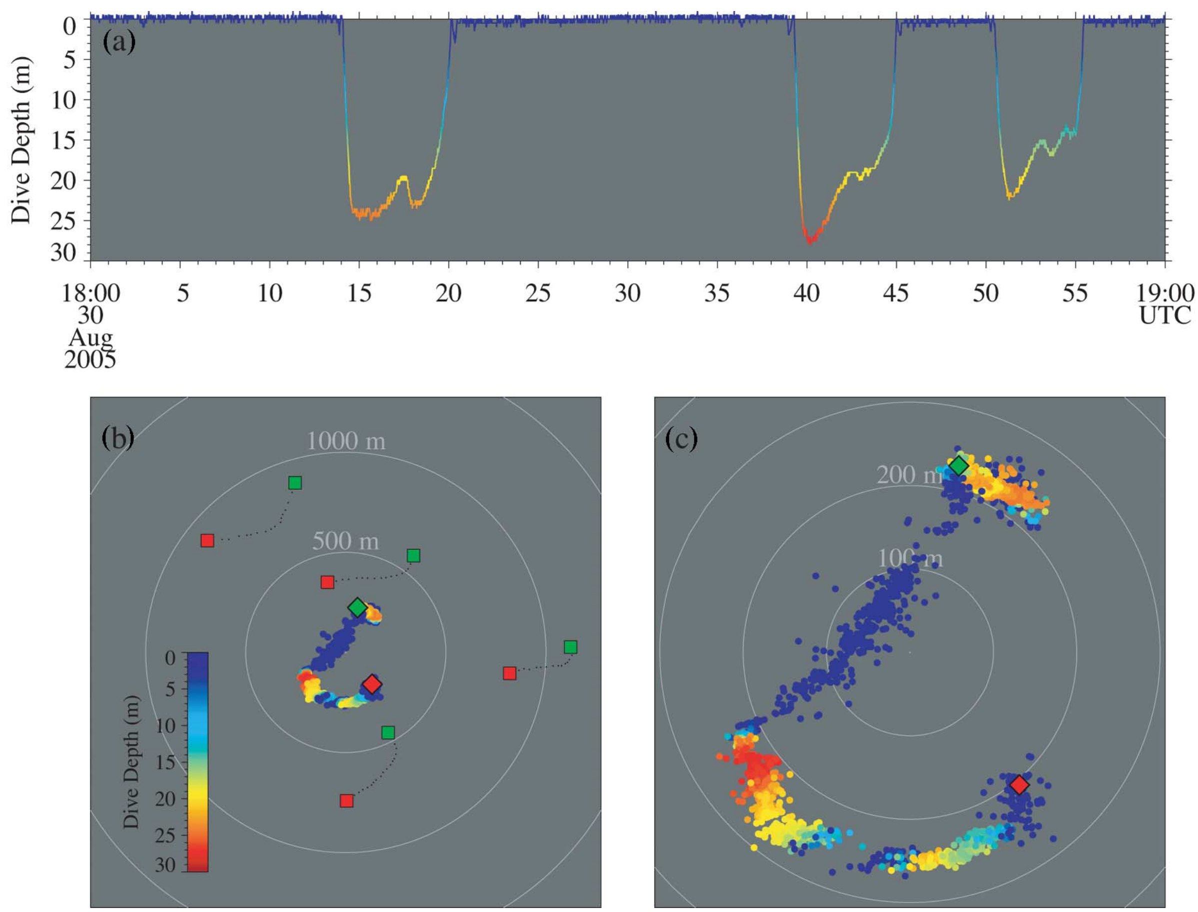

Fig. 9. (a) One hour of diving observations for a humpback whale tagged on August 30, 2005 in the Stellwagen Bank National Marine Sanctuary north of Provincetown, MA. Dive measurements acquired with a Wildlife Computers MK9 time–depth recorder incorporated in the tag. (b) Corresponding tracking data obtained with the RATS. Starting (green) and ending positions (red) of the buoys (squares) and the tagged whale (diamond) over the 1-h period are shown. Small filled circles indicate the RATS-derived track of the animal. Colors indicate the depth of the whale. (c) Closeup view of tagged whale's track.

(Fig. 6). The four-buoy solutions incorporate more time-of-arrival information and employ the iterative refinement (19), yet accuracy is only modestly improved over the three-buoy solutions. For both four- and three-buoy arrays, average accuracies of 7–9 m are less than a body length of all but the smallest of baleen whales, and are better than half of our originally specified accuracy of 20 m.

The depth of the transmitter was estimated by measuring the interval between successive ping receptions at each buoy (Δt) and applying (1). This resulted in four estimates of the transmitter depth (from each of the four buoys) for any given ping and, after comparison with the time-depth recorder, the associated errors (Table I). These four depth estimates are averaged in the localization algorithm to produce a single estimate of Z. RMS errors in the depth of the transmitter derived from the individual buoys were 3.06–3.69 m, but the averaged estimate had an RMS error of only 2.29 m (Table I). Biases in the depth estimates were less than the resolution of the time–depth recorder (0.5 m).

IV. EXAMPLE DEPLOYMENT

On August 30, 2005, we tagged an adult humpback whale in the Stellwagen Bank National Marine Sanctuary north of Provincetown, MA. The tag was attached via suction cup, and it carried a Wildlife Computers MK9 time–depth recorder, a radio transmitter, a Vemco V22P acoustic transmitter, and foam flotation. The tag was deployed at 13:11:00L from a 4.7-m rigid-hulled inflatable boat using a 9-m telescoping pole, and remained attached for 4 h and 23 min. The RATS array was maintained around the tagged whale during the entire deployment period. From 14:00:00L to 15:00:00L [18:00:00 to 19:00:00 coordinated universal time (UTC)], the whale spent over 70% of its time resting at the surface, engaging in only three dives [Fig. 9(a)]. Despite strongly stratified conditions (temperature decreased 10 °C in the upper 15 m of the water column) and long periods during which the transmitter remained near the surface, the system was able to resolve the whale's movements over spatial scales of tens of meters [Fig. 9(c)]. Most importantly, the RATS was able to provide this information in real time (Fig. 4) so that prey and oceanographic sampling could be conducted near the tagged whale even while it was submerged and out of view.

V. Conclusion

We have gained considerable field experience with the RATS in 2005 and 2006 during ongoing research on right and humpback whales. We found that maintaining the array of buoys around a mobile predator is particularly challenging if the tagged animal decides to travel elsewhere. It can take several minutes to reposition a single buoy, and we have encountered situations where the array simply cannot be repositioned quickly enough to keep up with a traveling animal. The system was designed to observe foraging behavior that is focused on a particular area, and the RATS has proven to be extremely useful under those circumstances. We are considering upgrades to the system to allow the small boats and the ship to carry hardware that will permit them to function as additional buoys, which should improve management of the array during brief bouts of traveling.

Given the very modest decrease in accuracy when using a three-buoy array instead of a four-buoy array, we now manage the RATS as if it were a three-buoy array and hold the fourth buoy in reserve for times when the animal moves out of the array. Upon deployment of the tag on a whale, three buoys are deployed in a triangular arrangement within 600–800 m of the tagging location. If the whale moves out of one side of this array, the fourth buoy is deployed such that a new triangular configuration is created around the whale. The outlying buoy is then retrieved and held until the whale moves out of this new array (e.g., if buoys 1–3 are initially deployed in a triangular array and the whale moves out of this array between buoys 2 and 3, then buoy 4 is deployed opposite buoys 2 and 3 to make a new triangular array around the whale, and buoy 1 is retrieved). It is sometimes useful to preposition this "spare" buoy in anticipation of particular swimming directions, but the inherent unpredictability of the animal's movements does not always make prepositioning effective. Managing the array by moving buoys in a small boat risks disturbing the tagged animal, but this can be mitigated by using a quiet, four-stroke outboard engine, traveling at moderate speeds, and continuously monitoring the whale's behavior for signs of disturbance. We have yet to detect overt reactions by whales to the presence of either our sampling vessel or the buoy-tender boat.

The accuracy of the RATS exceeded our original expectations, and our experience in the field has demonstrated that real-time continuous tracking can greatly facilitate prey and oceanographic sampling near a marine predator. In the example from August 30, 2005 described previously, we were able to collect observations of the fish schools upon which the tagged whale was feeding, the distribution and abundance of zooplankton and phytoplankton, and the physical properties of the water column using a side-looking, scanning multibeam sonar, video plankton recorder, optical plankton counter, fluorometer, and a conductivity–temperature–depth profiler. We are confident that these measurements will adequately characterize the feeding environment of the tagged whale because they were collected within meters to tens of meters of where the whale was foraging at depth. We anticipate that these kinds of collocated high-resolution observations will greatly improve our understanding of the ecology and habitat of top marine predators.

Acknowledgment

The authors would like to thank K. Houtler, captain of the *R/V Tioga*, and ship's mate I. Hanley for their gracious and tireless help during RATS testing and field research, and they recognize D. Ekstrand and M. Hunt, who developed the original localization equations and computer code, respectively, reported in [29] that were adapted for use here. The authors would also like to thank J. R. Buck and three anonymous reviewers for their help in improving the clarity of this paper.

References

[1] G. B. Skomal, G. Wood, and N. Caloyianis, "Archival tagging of a basking shark, *Cetorhinus maximus*, in the western North Atlantic," *J. Mar. Biol. Assoc. U.K.*, vol. 84, pp. 795–799, 2004.

[2] S. K. Hooker and R. W. Baird, "Deep-diving behaviour of the northern bottlenose whale, *hyperoodon ampullatus* (Cetacea: Ziphiidae)," *Proc. R. Soc. Lond., Ser. B: Biol. Sci.*, vol. 266, pp. 671–676, 1999.

[3] D. A. Croll, A. Acevedo-Gutiérrez, B. R. Tershy, and J. Urbán-Ramírez, "The diving behavior of blue and fin whales: Is dive duration shorter than expected based on oxygen stores?," *Comp. Biochem. Physiol., A*, vol. 129, pp. 797–809, 2001.

[4] A. Acevedo-Gutiérrez, D. A. Croll, and B. R. Tershy, "High feeding costs limit dive time in the largest whales," *J. Exp. Biol.*, vol. 205, pp. 1747–1753, 2002.

[5] W. A. Watkins, M. A. Daher, N. A. DiMarzio, A. Samuels, D. Wartzok, K. M. Fristrup, P. W. Howey, and R. R. Maiefski, "Sperm whale dives tracked by radio tag telemetry," *Mar. Mamm. Sci.*, vol. 18, pp. 55–68, 2002.

[6] K. L. Laidre, M. P. Heide-Joergensen, and R. Dietz, "Diving behaviour of narwhals (*Monodon monoceros*) at two coastal localities in the Canadian High Arctic," *Can. J. Zool.*, vol. 80, pp. 624–635, 2002.

[7] P. T. Madsen, R. Payne, N. U. Kristiansen, M. Wahlberg, I. Kerr, and B. Moehl, "Sperm whale sound production studied with ultrasound time/depth-recording tags," *J. Exp. Biol.*, vol. 205, pp. 1899–1906, 2002.

[8] M. F. Baumgartner and B. R. Mate, "Summertime foraging ecology of North Atlantic right whales," *Mar. Ecol. Prog. Ser.*, vol. 264, pp. 123–135, 2003.

[9] M. Johnson, P. T. Madsen, W. M. X. Zimmer, N. A. de Soto, and P. L. Tyack, "Beaked whales echolocate on prey," *Proc. R. Soc. Lond., Ser. B: Biol. Sci.*, vol. 271, pp. S383–S386, 2004, suppl. 6.

[10] R. W. Baird, M. B. Hanson, and L. M. Dill, "Factors influencing the diving behaviour of fish-eating killer whales: Sex differences and diel and interannual variation in diving rates," *Can. J. Zool.*, vol. 83, pp. 257–267, 2005.

[11] D. W. Sims, M. J. Witt, A. J. Richardson, E. J. Southall, and J. D. Metcalfe, "Encounter success of free-ranging marine predator movements across a dynamic prey landscape," *Proc. R. Soc. Lond., Ser. B: Biol. Sci.*, vol. 273, pp. 1195–1201, 2006.

[12] W. C. Burgess, P. L. Tyack, B. J. Le Boeuf, and D. P. Costa, "A programmable acoustic recording tag and first results from northern elephant seals," *Deep-Sea Res. II*, vol. 45, pp. 1327–1351, 1998.

[13] M. P. Johnson and P. L. Tyack, "A digital acoustic recording tag for measuring the response of wild marine mammals to sound," *IEEE J. Ocean. Eng.*, vol. 28, no. 1, pp. 3–12, Jan. 2003.

[14] S. K. Hooker and I. L. Boyd, "Salinity sensors on seals: Use of marine predators to carry CTD data loggers," *Deep-Sea Res. I*, vol. 50, pp. 927–939, 2003.

[15] D. A. Croll, B. R. Tershy, R. P. Hewitt, D. A. Demer, P. C. Fiedler, S. E. Smith, W. Armstrong, J. M. Popp, T. Kiekhefer, V. R. Lopez, J. Urban, and D. Gendron, "An integrated approach to the foraging ecology of marine birds and mammals," *Deep-Sea Res. II*, vol. 45, pp. 1353–1371, 1998.

[16] W. A. Watkins, K. E. Moore, D. Wartzok, and J. H. Johnson, "Radio tracking of finback (*Balaenoptera physalus*) and humpback (*megaptera novaeangliae*) whales in Prince William Sound, Alaska," *Deep-Sea Res.*, vol. 28, pp. 577–588, 1981.

[17] H. E. Winn, J. D. Goodyear, R. D. Kenney, and R. O. Petricig, "Dive patterns of tagged right whales in the great south channel," *Continent. Shelf Res.*, vol. 15, pp. 593–611, 1995.

[18] J. A. Lerczak, K. E. W. Shelden, and R. C. Hobbs, "Application of suction-cup-attached VHF transmitters to the study of beluga, *Delphinapterus leucas*, surfacing behavior in Cook Inlet, Alaska," *Mar. Fish. Rev.*, vol. 62, pp. 99–111, 2000.

[19] W. A. Watkins and W. E. Schevill, "Sound source location by arrival-times on a non-rigid three-dimensional hydrophone array," *Deep-Sea Res.*, vol. 19, pp. 691–706, 1972.

[20] B. Møhl, M. Wahlberg, and A. Heerfordt, "A large-aperture array of nonlinked receivers for acoustic positioning of biological sound sources," *J. Acoust. Soc. Amer.*, vol. 109, pp. 434–437, 2001.

[21] D. R. Ketten, "Functional analyses of whale ears: Adaptations for underwater hearing," in *Proc. IEEE OCEANS*, 1994, vol. 1, pp. 264–270.

[22] D. S. Houser, D. A. Helweg, and P. W. B. Moore, "A bandpass filter-bank model of auditory sensitivity in the humpback whale," *Aquat. Mamm.*, vol. 27, pp. 82–91, 2001.

[23] S. E. Parks, "Acoustic communication in the North Atlantic right whale (*Eubalaena glacialis*)," Ph.D. dissertation, Biol. Dept., Woods Hole Oceanogr. Inst., Woods Hole, MA, 2003, 266.

[24] D. R. Ketten, "Cetacean ears," in *Hearing by Whales and Dolphins*, W. W. L. Au, A. N. Popper, and R. R. Fay, Eds. New York: Springer-Verlag, 2000, pp. 43–108.

[25] W. A. Watkins, "Whale reactions to human activities in Cape Cod waters," *Mar. Mamm. Sci.*, vol. 2, pp. 251–262, 1986.

[26] A. S. Frankel, "Gray whales hear and respond to a 21–25 kHz high-frequency whale-finding sonar," in *Proc. 16th Biennial Conf. Biol. Mar. Mamm.*, San Diego, CA, Dec. 12–16, 2005.

[27] L. Freitag, M. Grund, S. Singh, J. Partan, P. Koski, and K. Ball, "The WHOI micro-modem: An acoustic communications and navigation system for multiple platforms," in *Proc. MTS/IEEE OCEANS*, 2005, vol. 2, pp. 1086–1092.

[28] L. E. Freitag, M. Grund, J. Partan, K. Ball, S. Singh, and P. Koski, "Multi-band acoustic modem for the communications and navigation aid AUV," in *Proc. MTS/IEEE OCEANS*, 2005, vol. 2, pp. 1080–1085.

[29] W. A. Watkins and W. E. Schevill, "Four hydrophone array for acoustic three-dimensional location," Woods Hole Oceanogr. Inst., Woods Hole, MA, Tech. Rep. 71-60, 1971, p. 33.

[30] W. H. Foy, "Position-location solutions by Taylor-series estimation," *IEEE Tran. Aerosp. Electron. Syst.*, vol. AES-12, no. 2, pp. 187–194, Mar. 1976.

[31] L. Freitag, M. Johnson, M. Grund, S. Singh, and J. Preisig, "Integrated acoustic communication and navigation for multiple UUVs," in *Proc. MTS/IEEE OCEANS*, 2001, vol. 4, pp. 2065–2070.

Mark F. Baumgartner was born on October 2, 1968 in Albany, NY. He received the B.S. degree in mathematics and computer science from the University of Notre Dame, Notre Dame, IN, in 1990, the M.S. degree in marine science from the University of Southern Mississippi, Hattiesburg, in 1995, and the Ph.D. degree in biological oceanography from Oregon State University, Corvallis, in 2002.

After two years as a Postdoctoral Scholar at the Woods Hole Oceanographic Institution, Woods Hole, MA, he joined the scientific staff there in 2005. Currently, he is an Assistant Scientist in the Biology Department. His research interests include the ecology of top marine predators (particularly baleen whales), the ecology of mesozooplankton, and physical–biological interactions that facilitate prey aggregation. His recent collaborative research has focused on baleen whale foraging ecology, mechanisms controlling diapause in calanoid copepods, and the application of autonomous underwater vehicles to the study of marine mammal ecology.

Dr. Baumgartner is a member of the Society for Marine Mammalogy, The Oceanography Society, and the American Geophysical Union.

Lee Freitag (M'88) received the B.S. and M.S. degrees in electrical engineering from the University of Alaska, Fairbanks, in 1986 and 1987, respectively.

Currently, he is a Senior Engineer at the Woods Hole Oceanographic Institution, Woods Hole, MA, where he has worked on projects related to underwater acoustics for almost 20 years. His research programs focus on underwater acoustic communication and navigation with a strong focus on unmanned underwater vehicles, sensors, and submarine systems.

Mr. Freitag is a member of the Marine Technology Society.

Jim Partan received the B.S. degree in physics from Williams College, Williamstown, MA, in 1994 and the M.S. degree in electrical engineering from the Massachusetts Institute of Technology/Woods Hole Oceanographic Institution Joint Program, Woods Hole, MA, in 2000. Currently, he is working towards the Ph.D. degree in computer science at the University of Massachusetts, Amherst.

He is also an Engineer at the Woods Hole Oceanographic Institution. He is interested in the intersection of networking, communications, and signal processing, and systems engineering for oceanographic instruments.

Keenan R. Ball was born on September 14, 1976 in Manchester, NH. He received the B.S. degree in electromechanical engineering from Wentworth Institute of Technology, Boston, MA, in 2000, and the M.S. degree in electrical engineering from the University of Massachusetts, Dartmouth, in 2002.

Currently, he is a Research Engineer in the Acoustic Communication Group, Applied Ocean Physics and Engineering Department, Woods Hole Oceanographic Institution, Woods Hole, MA. His research interests include the development of acoustic communication systems for autonomous underwater vehicles and oceanographic sensors as well as the development of technological systems to aid in the study of marine mammal communications.

Kenneth E. Prada was born on December 10, 1937 in Boston, MA. He attended the University of Massachusetts, Amherst, and from 1959 to 1963, he served a four-year enlistment in the U.S. Marine Corps.

In March 1966, he joined the technical staff of the Woods Hole Oceanographic Institution, Woods Hole, MA. His design and research interests involved computer and instrument systems for at-sea data acquisition and analysis, both hardware and software. He established a private consulting company in 1975 designing embedded computer applications for machine and process control. He retired as a Principal Engineer from the Woods Hole Oceanographic Institution in December 1997. His postretirement work supports both marine science and industrial instrument design. Since 2002, he has been contributing *pro bono* work for the marine science community.