



A programmable acoustic recording tag and first results from free-ranging northern elephant seals

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Abstract

A hydrophone-equipped tag recorded exposure to noise, as well as physiological and behavioral sounds, on free-ranging northern elephant seals (*Mirounga angustirostris*). The compact acoustic probe (CAP) consisted of the hydrophone, a thermistor, and a pressure transducer in a 36 cm long, 10 cm diameter cylindrical hydrodynamic housing capable of withstanding 2000 m depth. The enclosed logging electronics included a programmable “TattleTale 7” data acquisition engine and a 340 Mb hard disk. A custom low-power operating system supported multi-channel interrupt-driven sampling at 5 kHz. The complete tag weighed 0.9 kg in water and displaced 2.1 l. During five deployments on juveniles translocated from and returning to Año Nuevo, California, CAP tags measured dive pattern, ambient and vessel noise exposure, oceanographic ranging (RAFOS) and thermometry (ATOC) beacons, acoustic signatures of swim stroke, surface respiration, and cardiac function, and possible vocalizations. © 1998 Elsevier Science Ltd. All rights reserved.

1. Introduction

As the sounds of human activity in the oceans have intensified, so has concern about their effects on marine animals (Green et al., 1994; Richardson et al., 1995). The sounds of ship traffic alone raised marine noise levels by 10 dB between 1950 and 1975

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(Urlick, 1986), and now often dominate the 20–200 Hz band worldwide (Urlick, 1983). More recently, the development of high-power acoustic ranging, tomography, and telemetry systems heightened awareness of the potential impact of anthropogenic sound on ocean life (Munk and Forbes, 1989; Baggeroer and Munk, 1992; Cohen, 1991).

Despite this concern, the effects of anthropogenic noise on marine populations remain poorly understood. Payne and Webb (1971) and Myrberg (1980) pointed out that shipping noise may mask wildlife communication sounds, including sounds used for mating, with potential effects on reproduction. Bowhead and gray whales in shallow waters avoid sources of industrial noise (Malme et al., 1984; Richardson et al., 1985, 1986, 1990). Richardson et al. (1995) speculated that noise may also interfere with marine animals' navigation and feeding. Recent attention has focused on the potential exposure of deep-diving species to low-frequency sound, which propagates globally in the deep sound channel of temperate and tropical oceans. Unfortunately, deep diving also severely hampers scientific observation. Few methods have been available for biologists to learn what an animal hears a kilometer below the surface, or how it responds to noise at depth.

To address this need, we developed a recoverable tag that measures and stores acoustic, pressure, and temperature data over periods of several months from a free-swimming marine mammal. Based on a microcomputer and a hard disk (Fig. 1), the flexibility of the compact acoustic probe (CAP) allows its application to multiple species as well as to other oceanographic research. While the CAP mass-storage design requires recovery to access recorded data, it can support large acoustic data bandwidths that would be difficult or impossible for an expendable tag to telemeter from a diving animal with present technology.

Northern elephant seals, *Mirounga angustirostris*, were selected as the study platform for all initial CAP investigations. Seals regularly haul out on land, allowing easy access for attachment and recovery of tags. Elephant seals exhibit the greatest sensitivity to low-frequency sound of seals whose hearing has been tested, including harbor seals (Kastak and Schusterman, 1998). They experience a variety of acoustic environments during their migrations thousands of kilometers north and west from California (Le Boeuf et al., 1993). Elephant seals spend up to 90% of their time at sea submerged. They frequently dive to 500 m and occasionally to over 1500 m, and thus often encounter the sound channel (Le Boeuf et al., 1988; 1993).

Fletcher et al. (1996) used a commercial digital audio tape (DAT) recorder in a pressure housing to obtain the first acoustic data from free-swimming elephant seals. Their observations indicated the detectability of respiration and heartbeat at the surface and laid the foundation for the more complex tag described here. The DAT technique, however, did not support complex recording schedules or coordinated measurements with other sensors or events. The DAT tag provided less than 4 h of recording, required separate sensor and recorder packages to obtain pressure and temperature data, and did not provide accurate timestamps for data synchronization. The CAP can record both noise exposure and diving behavior during seal migrations of many weeks duration.

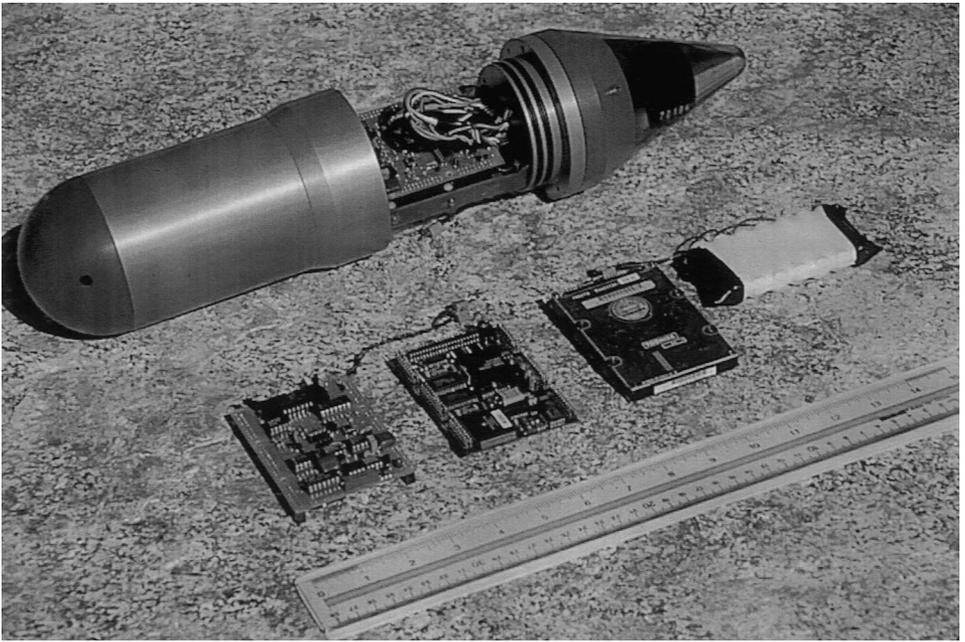


Fig. 1. The compact acoustic probe (CAP). Disassembled logger electronics are shown at bottom, including (from left to right) signal-conditioning board, Onset Computer Corporation “Tattletale 7” data acquisition engine, hard disk, and 7 alkaline AA cell battery pack. An assembled logger is shown at top, ready to be slid into the aluminum pressure housing. A PVC-and-resin tail cone at right contains the hydrophone, pressure transducer, and thermistor; only the hydrophone is visible in the photograph. A semispherical PVC cap reduces drag.

CAP deployments on elephant seals began in May 1995 and continue today. The data discussed here represent the first six deployments, made on translocated juveniles who were at sea from 1 to 11 days. Data from 70 to 120 day adult male migrations were recovered successfully in August 1997, and will be presented at a later time. Results from these experiments indicate that “hydrophone tags” such as the CAP may possess far broader measurement potential than originally envisioned. These results include detection of long-range 75 and 260 Hz acoustic beacons, acoustic measurement of swim stroke rate and respiration over extended periods, and acquisition of heart rate and phonocardiograms at depth as well as at the surface.

2. Tag design

2.1. Sensors and signal conditioning

Acoustic data were provided by an HTI-94-SSQB preamplified hydrophone with a sensitivity of -170 dB re 1 V/ μ Pa (High-Tech, Inc., Gulfport, Mississippi); temperature data by a Keystone “miniature sensor” thermistor (accuracy $\pm 1^\circ\text{C}$); and

pressure data by a PA-7-200 bridge transducer (Keller PSI, Oceanside, California). As configured and sampled in this application, the pressure transducer provided values accurate to ± 0.4 bar, or about ± 4 m depth. For the first deployment, a Logtron turbine speedometer (Flasch Electronic GmbH, Dachau, Germany) yielded estimates of speed. This mechanical speedometer was later dropped from the design because its turbine tended to foul or produce noise, and because the processor failed to maintain accurate acoustic sampling rates above 1 kHz when concurrently monitoring the speedometer.

A custom amplification and filtering circuit conditioned the hydrophone signals before analog-to-digital conversion. Two passive RC high-pass filters attenuated acoustic frequencies below 8 Hz. An initial gain stage amplified the signals by 0–31 dB of trimpot-adjustable gain; this first gain stage could be switched off by the software. The signals passed through a Linear Technologies LTC1164-6 switched-capacitor elliptic anti-alias filter (stopband -64 dB) whose filter cutoff frequency derived from the system clock. A final gain stage boosted signals by an additional 20 dB. Total post-sensor gain was set to 30 dB for all acoustic signals discussed here.

2.2. Data acquisition hardware

A “Tattletale 7” (TT7) data logger (Onset Computer Corporation, Pocasset, Massachusetts) controlled data acquisition, processing, and hard disk storage. The TT7, together with the signal-conditioning electronics and a 340 Mb hard disk, formed a compact package weighing 0.28 kg and measuring 11.3 by 7.0 by 4.5 cm (Fig. 1). The TT7’s analog-to-digital converter provided four-channel sampling with 12-bit resolution (72 dB dynamic range) over 4.096 V. Data buffering took place using 2 Mb of pseudo-static RAM and 180 kb of static RAM. The TT7 economized power consumption with sleep capability and variable processor speed, drawing approximately 6 W when spinning up the hard disk, 3 W when writing to the disk, 150 mW when sampling sound at 2 kHz, and 5 mW when idle. Because a disk write was necessary for every 2 Mb of acoustic data, the 2 kHz sampling rate required a disk access (24 s typical duration) for every 9 min of recording time. In cold water (5–8°C) these power drains limited active duty to 1 month on nine alkaline AA batteries; expected lifetime in warm water is two to four months.

An ICM7170 real-time clock with a dedicated crystal provided timestamps accurate to ± 2 s for all data presented. Because all data channels were sampled against the same time reference, they could be compared to each other independent of clock accuracy. Applications that depend on accurate timekeeping, such as position-fixing using acoustic beacons, could be accommodated in the future by using a higher-quality, temperature-stabilized crystal, and by setting the clock with improved precision.

2.3. Software

A custom operating system controlled all aspects of data acquisition and storage. Written in C and Motorola MC68000 assembly language, the operating system

acquired acoustic data at sampling rates of up to 5 kHz using interrupts, or up to 100 kHz using a dedicated wait loop. Use of interrupt-based sampling allowed the main program to inspect or compress data during acquisition while preserving accurate sampling rates. For this application, compression demanded excessive power and was not used.

Additional savings in power resulted from the use of one, rather than two, write buffers for acoustic data. Each time the buffer filled, sampling ceased temporarily and the buffer flushed to disk. While this approach created periodic gaps in the acoustic record of about 24 s, the time required to spin up the disk and write 2 Mb of acoustic data, it also saved power compared with double buffering by requiring half the number of disk write cycles.

2.4. Sampling schedule

The experiments described here sampled pressure and temperature at 5 s intervals throughout the deployment, and sampled the hydrophone at 1 or 2 kHz continuously (except for disk write gaps) during specified acoustic recording windows. Choice of recording windows varied with application. The first two deployments recorded every fourth dive, including the preceding and following surface intervals, at a 2 kHz sampling rate; in addition, 15 min segments corresponding to the transmission time of West Coast “RAFOS” acoustic beacons (Garfield et al., 1997) were recorded at a 1 kHz rate. In all subsequent deployments, acoustic data were acquired continually after release at a 2 kHz rate. Sampled at this rate, acoustic data filled the 340 Mb hard disk after 24 h of data acquisition.

2.5. Enclosures

We employed two different pressure housing designs to contain the sensors and electronics. The first, a rectangular box weighing 2.4 kg complete and capable of withstanding 1000 m depth, served for the first four pilot deployments. We potted the hydrophone in a semicylinder of GE RTV615 silicone attached along its flat side to the enclosure bulkhead. After two deployments, electrical problems with pressure, temperature, and speed sensor connections forced us to repot the hydrophone without other sensors, this time using Courtaulds Aerospace PR1570 polyurethane and a tapered cylinder mold.

Our experience with the rectangular enclosure led us to design a second enclosure based on a 10 cm outside diameter aluminum cylinder (Fig. 1). The cylindrical tag weighed 3.0 kg in air or 0.9 kg in water, and was designed to withstand up to 2000 m depth. Stronger per unit weight than the rectangular enclosure, the cylindrical shape also facilitated fabrication and the robust attachment of sensors. All sensors resided within an interchangeable conical PVC-and-polyurethane “sensor pack” which simply screwed on to the cylinder bulkhead. All three configurations of the CAP located the hydrophone at the aft end of the housing to reduce flow noise (Fletcher et al., 1996).

3. Field methods

Six juvenile elephant seals (Table 1) were captured at Año Nuevo State Reserve, CA, either in spring before molting, or in fall before the winter juvenile foraging migration

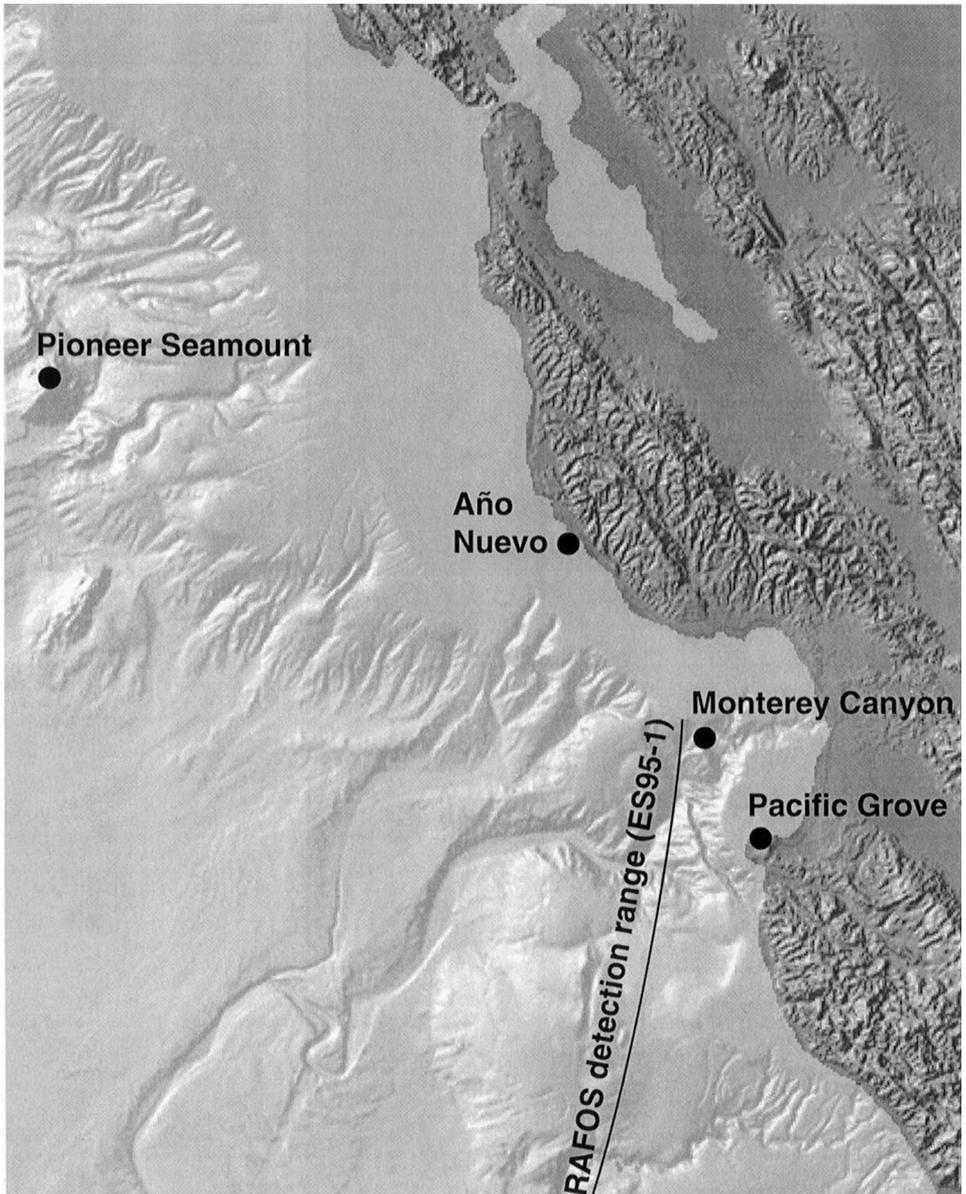


Fig. 2. Locations of capture, release, and recovery. The line indicates a time-of-arrival range fix from a RAFOS sound source to subject ES95-1; see the section on RAFOS detection in the text.

(Le Boeuf et al., 1996). The subjects were immobilized with Telazol (Aveco Co. Ltd., Fort Dodge, IA) and ketamine hydrochloride. They were then transported to the Long Marine Laboratory of the University of California at Santa Cruz, 30 km south of the reserve.

A CAP tag was fitted to each subject using hose clamps glued to the pelage with marine epoxy (Evercoat Ten-set, Fibre-Evercoat Co., Cincinnati, OH). Mount integrity was assured using either a minimum 1 cm layer of epoxy or a nylon mesh reinforcing a thinner epoxy layer (Le Boeuf et al., 1988). In both cases the CAP stood off the subject's back by at least 1 cm. All subjects carried Argos system satellite transmitters (Telonics Inc., Mesa, AZ), attached in a similar fashion to the tops of their heads, to provide notification of haul-out. Subjects ES96-1 and ES96-2 carried separate dive recorders, because the CAP unit used for those subjects measured acoustics only.

ES95-1 was transported by truck to Pacific Grove and released on shore. All other subjects were released from a boat, either over the Monterey Canyon or over Pioneer Seamount (Fig. 2).

4. Results and discussion

Five of the six juveniles returned to the Año Nuevo rookery after a median of three days at sea (Table 1). Diving behavior generally consisted of continuous submergence to depths reaching 900 m, punctuated every 10–20 min by brief (2 min typical) surface intervals. These observations were consistent with previous studies of juvenile elephant seals (Le Boeuf et al., 1996). Sounds characteristic of flow noise, swim stroke, vessel noise, and, at the surface, respiration and heartbeat, dominated the acoustic record. ES96-1 and ES96-2 recorded vocalizations from other marine species. These

Table 1
Initial CAP deployments on Juveniles, May 1995–April 1996

Name	Release (Date)	Location	At sea (Days)	Enclosure	Hydrophoner housing
ES95-1	5/8/95	Pacific Grove	3	Rect. ^a	Semicyl.
ES95-2	10/1/95	Monterey Canyon	1	Rect. ^b	Semicyl.
ES96-1	4/8/96	Pioneer Seamount	2	Rect. ^{c,d}	Tapered cyl.
ES96-2	4/22/96	Pioneer Seamount	11	Rect. ^{c,d}	Tapered cyl.
ES96-3	4/22/96	Pioneer Seamount	^c	Cyl. ^d	Cone
ES96-4	4/29/96	Pioneer Seamount	5	Cyl. ^d	Cone

^a Speedometer fouled after 1.5 hours.

^b Intermittent failure of all sensors; some recording in air at Año Nuevo.

^c No built-in dive recording (separate dive recorder used).

^d No built-in speedometer.

^e ES96-3 hauled out in the Farallon Islands and was inaccessible for recovery.

signatures were consistent with those documented by Fletcher et al. (1996) and, with the exception of flow noise and surface heartbeat, will not be treated in detail here. Beyond these dominant sounds, however, the CAP acoustic data and subsequent processing also revealed signals from RAFOS and ATOC beacons, heart sounds at depth, and possible vocalizations by the subject or a conspecific.

4.1. Flow noise

Flow noise imposes a fundamental limit on the utility of hydrophone tags: at high subject velocities, low-frequency flow noise may obscure other acoustic data or saturate the recorder. The ability to predict how flow noise will vary with swim speed and the shape of the hydrophone package is therefore essential to the design and useful application of hydrophone tags.

Fig. 3 plots the relationship between recorded flow noise and speedometer measurements from ES95-1. The data were obtained during the initial 16 min of the first deployment, the only period for which we have reliable and coordinated data from both acoustic and speed CAP sensors. Flow noise was evaluated between 8 and 18 Hz, where the strength of flow noise relative to ambient noise was greatest and therefore the most practical to study. This acoustic band was isolated by an 8 Hz high-pass filter in the acquisition electronics and an 18 Hz low-pass filter applied in postprocessing. The envelope of the remaining 13 ± 5 Hz band was sampled instantaneously at 5 s intervals to correspond with the speedometer sampling. We calculated speed from the speedometer turbine rotation rate using the calibration values of Fletcher et al. (1996). This calibration must be applied with caution, for even though our speedometer was identical to that used in the earlier study, speedometers typically exhibit extreme sensitivity to placement and orientation from one case to another (Blackwell et al., 1998).

The results suggest that the speedometer may have frequently underestimated swim speed. Even when the speedometer indicated slow swim speeds, flow noise at 13 Hz often exceeded $120 \text{ dB re } 1 \mu\text{Pa}^2/\text{Hz}$. Such strong flow noise would be inconsistent with the low speeds measured; however, no other noise sources could be identified by listening to the record. The discrepancy may be due to frequent obstruction of speedometer flow, either by the enclosure—the speedometer was located on its side rather than its top—or by the body of the subject.

The observed variation of flow noise with speed compared well with an independent prediction. The solid line in Fig. 3 shows an independent empirical function of flow noise versus speed presented by Finger et al. (1979). Their studies showed that, for a pressure hydrophone mounted on the aft end of a 10.2 cm diameter cylinder towed perpendicular to its axis, flow noise could be expected to increase by 18–21 dB with every doubling of speed (i.e. an approximately cubic relationship). We used 18 dB per speed doubling, and fixed the curve with a value of $70 \text{ dB re } 1 \mu\text{Pa}^2/\text{Hz}$ at 0.25 m/s as given for 13 Hz in Fig. 6 of Finger et al. (1979). The shaded region of Fig. 3 identifies speedometer readings less than the speed estimated from flow noise. Many of the readings fall within the shaded region, consistent with frequent obstruction of speedometer flow. Data points outside the shaded region may reflect the differences in

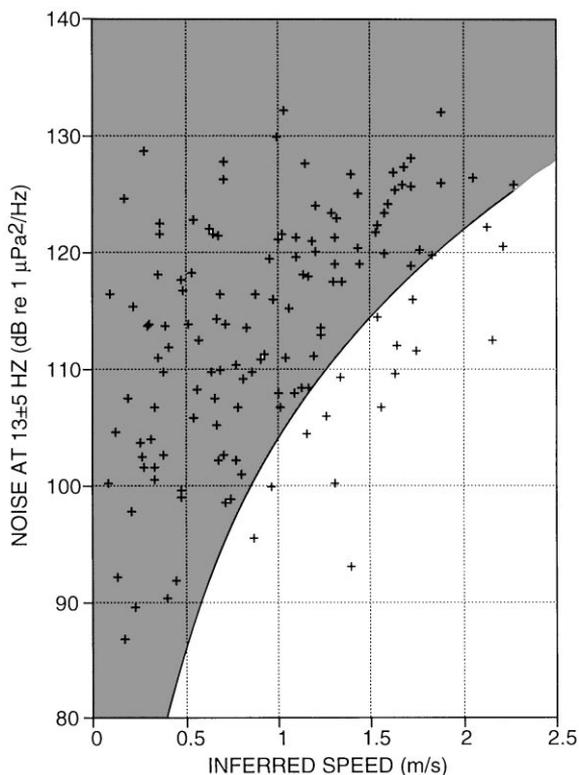


Fig. 3. Flow noise at 13 ± 5 Hz as a function of swim speed. Speed was inferred from speedometer rotation rate using the calibration of Fletcher et al. (1996). The solid line, taken from Finger et al. (1979), predicts an 18 dB increase in flow noise for every doubling of speed and is independent of the data presented. Data points in the shaded region indicate speedometer readings equal to or less than the speed predicted from corresponding flow noise. Data points corresponding to zero speedometer rotation rate (i.e. speedometer stalled) are not plotted. Juvenile elephant seals swim at a mean of 1 m/s, with the greatest speeds occurring near the surface on ascent and descent (Fletcher et al., 1996).

flow characteristics between our hydrophone enclosure and the cylindrical body tested by Finger et al. (1979).

Flow noise also varied with frequency and with the three hydrophone housing shapes used. To compare absolute flow noise levels from one deployment or housing to another requires complete velocity information, which we do not possess for these deployments. Nevertheless, we can compare relative behavior of flow noise with frequency for the three housing shapes. Twelve 10 s segments of flow noise were selected for analysis, four each from ES95-1, ES96-1, and ES96-4. To minimize confusion with ambient noise, selections were made from the loudest flow noise observed. Such flow noise generally occurred just before the subject returned to the surface. A Fourier transform was applied to each of the 12 segments, and the four results for each housing shape were averaged together, filtered with a 16-point moving average for clarity, and plotted in Fig. 4.

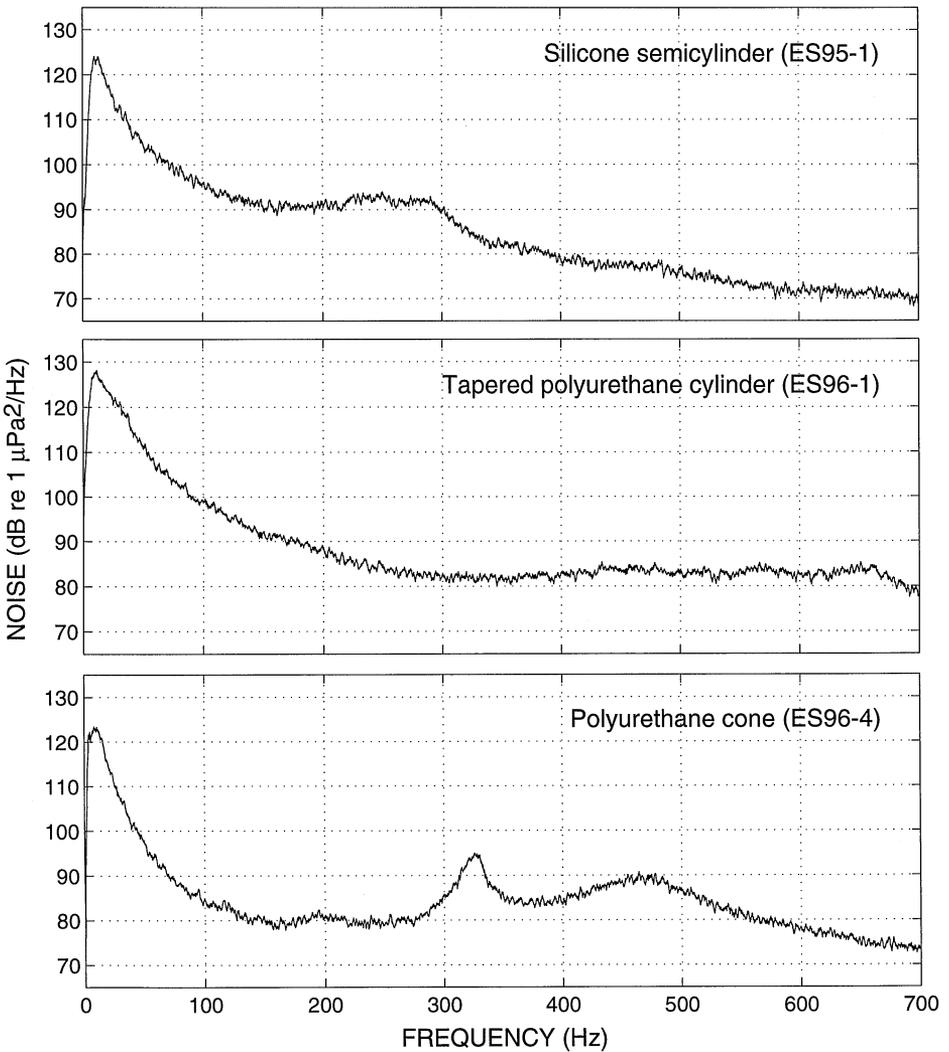


Fig. 4. Worst-case flow noise for three different hydrophone housing shapes. Typical flow noise during slower swimming measured 10–30 dB less. Absolute levels must be compared with caution, as maximum swim speeds for the three subjects may have differed.

For the semicylinder and tapered cylinder hydrophone housing shapes, flow noise from 10 to 100 Hz decreased by 10 dB per octave. This decrease is consistent with that shown in Fig. 6 of Finger et al. (1979) for a pressure hydrophone facing aft in a cylindrical housing. Cone flow noise compared favorably with that of the other shapes below 100 Hz, falling off by 13 dB per octave; between 300 and 350 Hz, however, cone noise increased again. This secondary peak may be due to “whistling”, either from screw access holes in the cone’s PVC base, or from the mount hardware,

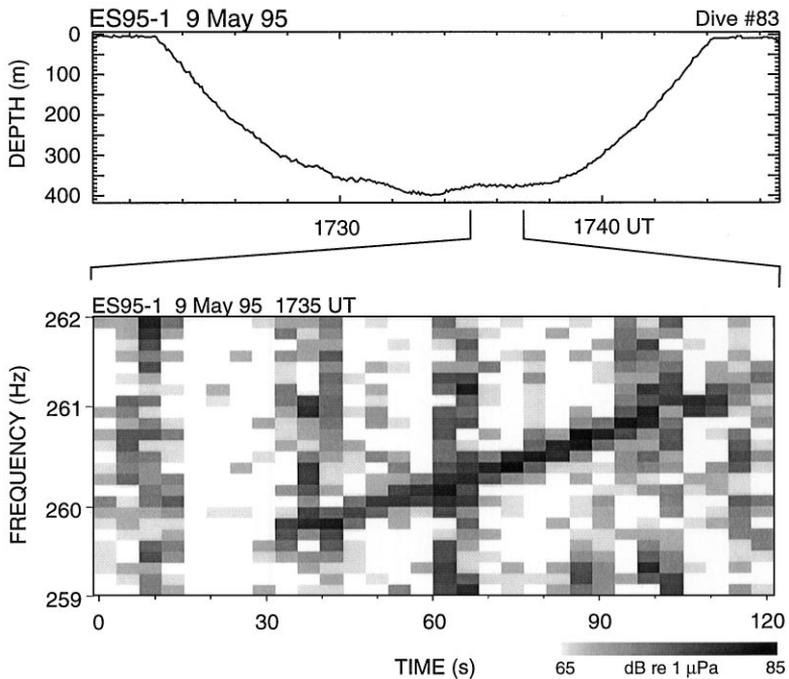


Fig. 5. ES95-1 reception of a RAFOS ranging broadcast. The signal-to-noise ratio was approximately 18 dB. A partial position fix calculated from the time of arrival and assuming a sound speed of 1500 m/s is shown in Fig. 2.

including hose clamps and support shims. Likewise, the bulge in flow noise at 250–300 Hz for the semicylinder may have resulted from enclosure attachments, including in that case a VHF radio beacon.

4.2. RAFOS

For over a decade, physical oceanographers have used deep-drifting RAFOS floats to track ocean currents (Rossby et al., 1986). These floats, named for the reverse of “SOUND Fixing And Ranging”, receive acoustic signals from a system of moored beacons to fix their position. We partially localized subject ES95-1 using the same signals.

On its first two deployments, the CAP was programmed to record transmissions from four Webb standard RAFOS sound sources moored off the West Coast (Garfield et al., 1997). Each source broadcasts an 80 s swept-frequency pulse twice daily with a starting frequency of 259.375 Hz, an upswEEP of 1.523 Hz, and a source level of 183 dB re 1 μPa at 1 m. A total of 25 15-minute acoustic periods coinciding with RAFOS transmission times were recorded. Each period was matched filtered against a synthesized RAFOS pulse. One of the cases exhibited a post-filter peak 18 dB above the surrounding noise. We confirmed this as a RAFOS detection by inspection of a spectrogram (Fig. 5). The signal arrived at the seal at a level of 84 dB re 1 μPa, 330 s

after transmission from a RAFOS source located at $37^{\circ}06.55'N$, $127^{\circ}34.60'W$. If for the purpose of discussion we assume a sound speed of 1500 m/s, this propagation delay places the seal 495 km from the RAFOS source. This range, combined with the seal's 370 m depth at detection time, suggests a location south of the continental shelf break somewhere along the line plotted in Fig. 2.

None of the remaining 24 RAFOS periods examined with matched filtering showed evidence of a signal. Of these 24 periods, 13 occurred when the subject was in relatively shallow shelf water and well out of the sound channel used by RAFOS. Nine more corresponded to beacons located 380–1000 km up or down the coast from the beacon which was successfully observed; coastal bathymetry in Monterey Bay may have blocked reception of these other beacons. For the two remaining periods, the seal was near the surface at the most likely reception time and thus again out of the sound channel.

4.3. ATOC

The four CAP deployments in April 1996 coincided with transmissions from the California source of the Acoustic Thermometry of Ocean Climate (ATOC) experiment (Forbes, 1994). This source was located at Pioneer Seamount, 80 km west of Half Moon Bay, California, at a depth of 937 m (Howe, 1996). It broadcast a phase-modulated m-sequence with a center frequency of 75 Hz, a bandwidth of 37.5 Hz, and a source level of 195 dB re $1 \mu\text{Pa}$ at 1 m; the 25-min transmissions began at 165 dB, were ramped up in five 1-min, 6 dB steps, then continued at full power for 20 min before ceasing (Howe et al., 1995). The broadcasts occurred every 4 h on a transmission day.

The subjects were transported by boat to a location 1–2 km northwest of the seamount and deployed 30–90 min before ATOC transmission. The subjects' direct return path from this area to the rookery at Año Nuevo lay directly over the seamount, thus maximizing their potential exposure to the ATOC source. Three of the four ATOC CAP deployments were recovered, all of which recorded the ATOC signals at maximum received levels of 118–130 dB re $1 \mu\text{Pa}^2/\text{Hz}$, or 124–136 dB re $1 \mu\text{Pa}$ in the 37.5 Hz transmission band. As a preliminary investigation of the stimuli experienced by the subjects, and of any associated response, we have analyzed the first and strongest ATOC reception from ES96-4.

Fig. 6 shows 195 min of dive data, beginning with the subject's departure from the deployment boat, and a 42 min window of acoustic data including the 25 min ATOC transmission. During much of the 5 min ramp-up period the seal was at the surface, and the ATOC signal arrived only faintly because of the acoustic pressure-release nature of the sea–air boundary. The subject first encountered ATOC levels above ambient noise upon diving at 1559 universal time (UT). Received ATOC levels reached 126 dB re $1 \mu\text{Pa}$ during this short dive. During the seal's following dives, received levels ranged from 101 to 131 dB re $1 \mu\text{Pa}$. The ATOC broadcast terminated at 1620 UT.

Three readily evaluated measures of response suggest no obvious effect of ATOC on the subject. First, dive behavior during ATOC exposure was consistent in both

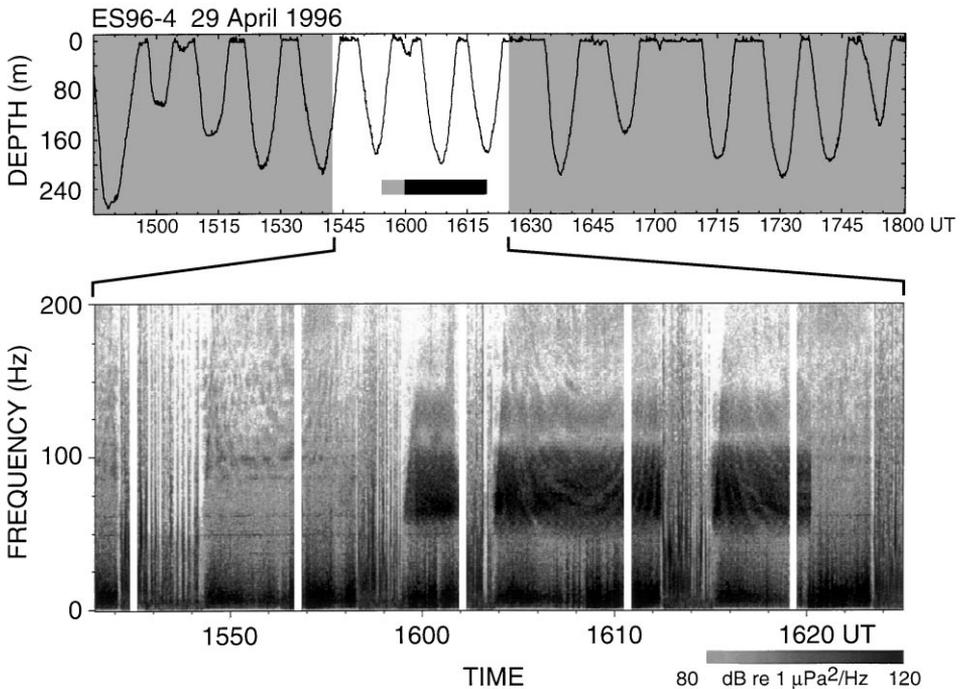


Fig. 6. ATOC as observed during diving by seal ES96-4. The upper panel shows 195 min of dive behavior, starting with the subject's departure from the deployment boat at 1445 UT. The unshaded dive data corresponds to the spectrogram in the lower panel. As indicated graphically by the shaded bar, the ATOC source commenced broadcasting shortly after 1554 UT, gradually increased its strength by 30 dB over the next 5 min to reach a source level of 195 dB re $1 \mu\text{Pa}$ at 1 m, then terminated at 1620 UT. Flow noise, dominating below 40 Hz, indicates relative speed at depth (see Fig. 3). Close examination of flow noise at 1620 UT shows that speed increased before, not after, ATOC termination. At the surface, respiratory sounds dominated the record.

depth and duration with other dives recorded during this deployment (the short dive at 1559 UT, while coincident with the subject's first exposure to ATOC, was similar to other short dives observed at times when ATOC was off). Second, while the ATOC signal was virtually absent at the surface and omnipresent at depth, the subject's surface intervals during exposure to ATOC did not exceed the 2–3 min typical of juvenile elephant seals (Le Boeuf et al., 1996). Third, flow noise measurements did not indicate sudden changes of speed in association with ATOC's final 5 dB increase to full power at 1600 UT, nor with signal cessation at 1620 UT (close examination shows that the flow noise increase observed near 1620 UT occurred before rather than after signal cessation).

Finally, we note that the observed ATOC signal minima and maxima depend on both depth and frequency. Minima and maxima result from the interference of multiple signal ray paths originating from the source and reflecting at the surface and bottom. For narrowband tone signals, this interference results in a strong dependence

of observed signal strength on location as one moves through nulls and peaks in the interference pattern. Because interference structure also depends on wavelength, broadband signals such as ATOC exhibit different spatial null patterns at different frequencies as demonstrated in Fig. 6. These complications must be taken into account when evaluating depth- and range-dependent behavior as a potential indicator of response to narrowband and broadband signals. Direct measurement of acoustic stimuli at the subject is particularly important where such complexities of acoustic propagation render it difficult to predict what a subject will hear.

4.4. *Cardiac function*

Fletcher et al. (1996) recorded pulses consistent with heart beat during the surface intervals of DAT-bearing elephant seals. Initial analysis of CAP data suggests that elephant seal cardiac activity produces sound at depth as well, only at frequencies near the lower limit of human hearing and occupying the same band as the loudest flow noise. That both studies observed acoustic cardiac signatures is supported by the results of a laboratory experiment conducted in March 1996, in which a bench-mounted CAP logger acquired simultaneous acoustic and electrocardiogram signatures from a captive juvenile elephant seal submerged in a tank (Burgess et al., 1996). Fig. 7 shows acoustic examples of cardiac function selected from ES95-1 during periods with no evident flow noise. The cases demonstrate the substantial physiological adjustments associated with dive behavior as well as the potential of acoustic measurements to assess these adjustments.

Fig. 7a represents typical eupnea, during which respiratory sounds were interspersed with heart sounds occurring at 120 beats per min. Each respiration cycle was associated with a transient broadband (10–200 Hz) hiss combined with three loud impulses, consistent with field and laboratory observations by Fletcher et al. (1996). To investigate the cardiac signatures in greater detail, beats not influenced by respiratory or other noise were averaged (middle panel) using a matched filter to provide a consistent time reference for superposition. Neighboring heart beats and respiratory impulses contaminated the beginning and end of the average and are shown in gray. The bottom panel displays a phonocardiogram (Rangayyan and Lehner, 1988) generated from the averaged cardiac signature using 256-point short-time Fourier transform windows with 87.5% overlapping. Fig. 7b and 7c show similarly processed data for an apneic surface interval (60 beats per min) and an 80 m dive (42 beats per min), respectively.

Dramatic differences existed among the three cases. At the surface, when the seal replenished its supply of oxygen, heart rate reached its maximum. The two heart sounds, associated with closure of the mitral and aortic valves (Rangayyan and Lehner, 1988), occurred too close together to be distinguished easily; but combined they approached peak levels of 116 dB re 1 μ Pa at frequencies reaching 150 Hz. With apnea, however, significant changes to the cardiac signature occurred. Heart rate halved (bradycardia), the peak level of the first heart sound decreased by 4 dB, and maximum frequency dropped to 100 Hz. The two-sound structure expanded temporally, and a 10 dB difference could be observed between the stronger first sound and

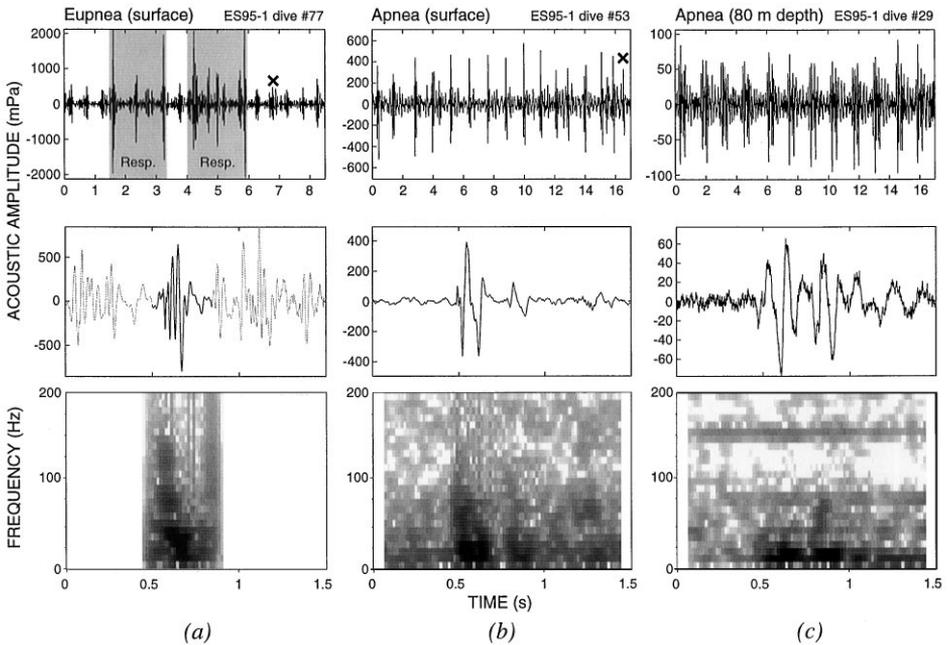


Fig. 7. Examples of cardiac function obtained from a free-ranging juvenile seal (ES95-1) during (a) eupnea, (b) apnea at the surface, and (c) apnea at 80 m depth. Top panels show acoustic waveform excerpts; these have been low-pass filtered at 40 Hz for clarity, but even before filtering, cardiac (and, in eupnea, respiratory) signatures dominated each record. Each panel in the middle row shows a superposed cardiac signature, averaged from all beats in the panels above it except noisy beats shaded or marked with an x, and low-pass filtered at 300 Hz. Lower panels show phonocardiograms generated from the superposed signature.

the weaker second sound. Finally, at 80 m depth, heart rate decreased an additional 30% relative to surface apnea. The first and second heart sounds now exhibited similar peak levels of about 92 dB re 1 μ Pa, and their peak frequencies fell to 30 Hz.

Interpretation of these observations requires caution. To our knowledge phonocardiogram (PCG) analysis has never been applied to the study of diving physiology; indeed, it remains a current research topic for human physiology. Wood and Barry (1995), for example, recently reported new analyses indicating that the first human heart sound originates from the acceleration of myocardial contraction as well as from valve-initiated myocardial waves. If this conclusion can also be applied to seals, the significant drop in peak heart sound amplitudes and frequencies observed at depth (Fig. 7c) may reflect decreased stroke volume and blood flow during diving, consistent with reduced metabolism and peripheral vasoconstriction (Elsner and Gooden, 1983). Likewise, at the surface, the relatively small 4 dB decrease in heart sound levels associated with the transition to bradycardia (Fig. 7b) may indicate a relatively constant stroke volume despite halving of the heart rate. A lack of strong correlation

between stroke volume and heart rate would be consistent with prior studies of harbor seals, *Phoca vitulina*, by Ponganis et al. (1990).

Other aspects of the cardiac signatures also merit mention. The weakened first heart sound while diving, for example, may reflect an increase of blood pressure consistent with vasoconstriction (D. Barry, *personal communication*). Also, the low-frequency “ringing” persisting at least 0.5 s after the second heart sound at depth may arise from the response of other tissues to the acoustic impulse of myocardial contraction. If so, this ringing may contain information on tissue content.

The utility of recording physiological acoustics *in vitro* stems from the excellent impedance match between living tissue and water. Medical researchers attempting to identify artificial heart valve malfunctions acoustically have recently exploited this effect by recording heart sounds from a hydrophone near a submerged patient (Reynolds and Stephen, 1995). Many other species may lend themselves to such analyses. The heartbeat of an immobilized juvenile leopard shark, for instance, was detected at a fundamental frequency of 10 Hz using a CAP hydrophone held against its abdomen (W. Burgess, H. Dewar and P. Tyack, *unpublished data*).

Deliberate hydrophone measurements of underwater physiological sounds may require careful tag placement. In particular, if physiological sounds couple mechanically through the tag mount instead of acoustically through the water, reception could depend heavily on a hydrophone tag’s location. Our data, however, are not consistent with significant transmission of physiological sounds through the tag mount. Data from ES95-2, which accidentally recorded in air after haul-out, do not show signatures in air similar to the respiration and heart beat signals recorded while at sea.

4.5. Heart rate during exposure to vessel noise

Subject ES95-1 encountered vessel noise several times during its journey from Pacific Grove to Año Nuevo. The loudest recorded period of vessel noise coincided with a dive in which no flow noise was observed during the time between descent and ascent. This lack of flow noise presented an opportunity to extract the relatively weak heart signals from the acoustic data. We matched filtered the data using the superposed cardiac signature from Fig. 7c as a kernel.

Fig. 8 compares the results of this analysis for two dives: Dive #13 with vessel noise, and Dive #29 which was extremely quiet and from which the matched filter kernel signature was obtained. For both dives the flat characteristic of the dive record, shown at top, together with that of neighboring dive records, suggests that the seal was located at or near the sea floor. Also for both dives, lengthy gaps in the flow noise (middle panels) indicate swim slowing or cessation (see Fig. 3). In the absence of flow noise, the matched filter successfully extracted instantaneous heart rate from both cases (lower panels, diamonds) to which a nine-point moving average was applied (lower panels, solid line). When flow noise was present, however, as in the subject’s ascent and descent, it prevented the simple matched filter technique from producing meaningful results. More complicated signal processing approaches may be necessary to improve heart rate detectability in the presence of flow noise.

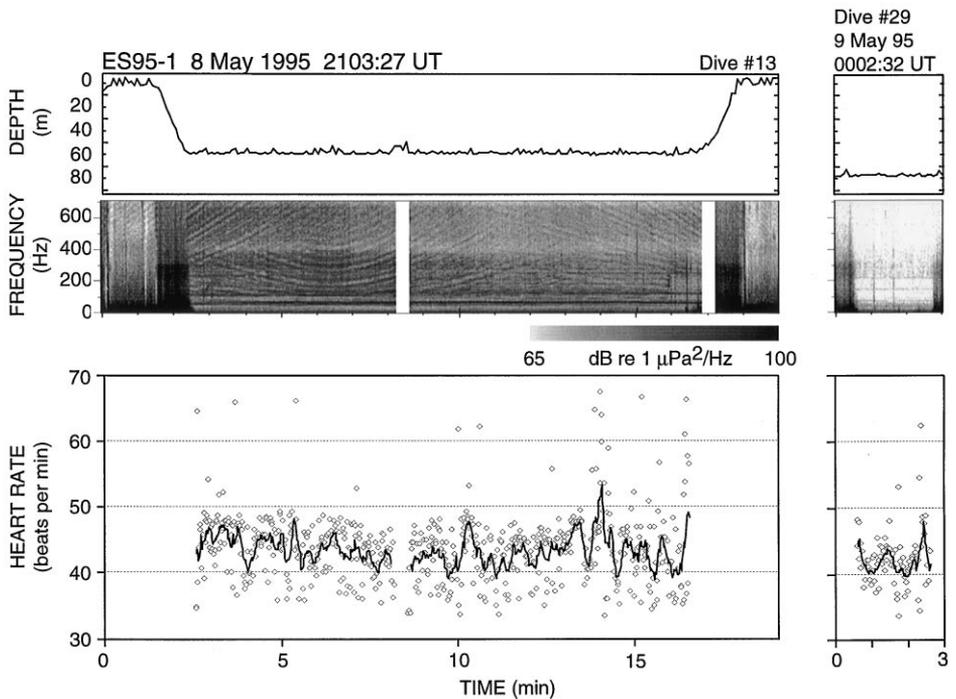


Fig. 8. Acoustically determined heart rate of ES95-1 during the passage of nearby vessels. Panels at left (Dive #13) show a dive during which boat noise reached the subject at levels extending to 100 dB re $1 \mu\text{Pa}^2/\text{Hz}$. The curvilinear spectral patterns resulted from changes in the noise interference geometry as the vessels passed by, with the “minimum” indicating the closest point of approach. Panels at right (Dive #29) show a quiet period during a later dive.

Extended cessation of submerged swimming in shallow water represents a departure from typical behavior observed both in the past (Le Boeuf and Crocker, 1996) and during this study. In over 7 h of shallow-water acoustic recordings from ES95-1 (the only deployment which obtained useful shallow-water data) we found only three instances of swim-speed reduction lasting more than one minute. Of these, the 14 min (Dive #13) and 2 min (Dive #29) instances shown in Fig. 8 were the two longest. Despite this suggestion of a behavioral response to the vessel, no obvious changes in heart rate occurred in association with vessel movements, nor was any general elevation or depression of heart rate evident relative to the quiet period in Dive #29. This lack of physiological response despite an apparent behavioral response may indicate an uncertain role for heart rate as a response indicator for elephant seals. On the other hand, since Dive #29 does not represent baseline behavior, it may not adequately represent baseline physiology either; both cases shown may involve response to an external stimulus, such as another vessel or

a predator, although no such stimulus was identified in the data available for Dive #29.

4.6. Possible vocalization

Nine acoustic signatures were observed on ES95-1 that exhibited marked similarity to adult male elephant seal threat calls. The signatures occurred during only two dives, separated by 90 min, out of the 50 dives recorded by ES95-1. The dives involved descents with unusually low flow noise, approximately 80 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ at 10 Hz, occurring between 220 and 420 m depth. The dive record showed these two dives to be consistent with “drift” (or “process”) dives (Le Boeuf et al., 1992; Crocker et al., 1997) in which the seal dives or sinks at a slow, relatively constant rate for most of its descent. The nine signatures—seven strong (peak 93–100 dB re 1 μPa) and 2 weak (peak 83 dB re 1 μPa)—may represent underwater vocalizations from the juvenile female subject or from a conspecific.

Fig. 9 compares one of the strong putative vocalizations with a terrestrial vocalization recorded, but not necessarily produced, by subject ES95-2 in air at the Año

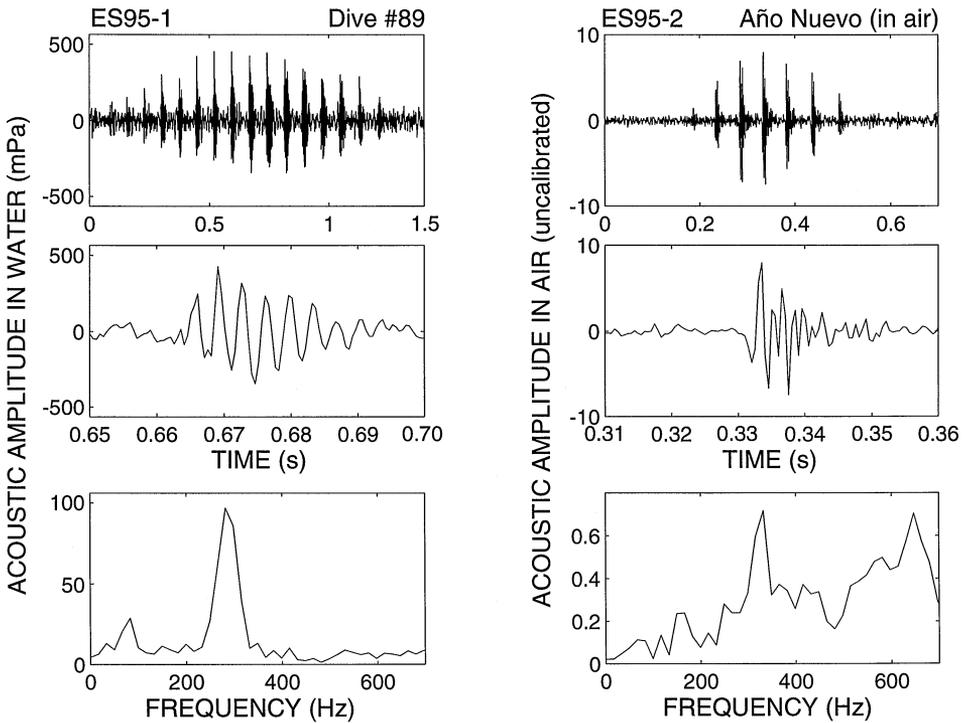


Fig. 9. Comparison of a putative vocalization, recorded at 366m depth by a juvenile female seal (ES95-1), with a vocalization in air recorded by ES95-2 at the Año Nuevo rookery. For clarity, the time scale of the upper right panel is expanded compared with that at upper left.

Nuevo rookery. Both signatures consist of a train of clicks, evenly spaced by 75 ms in water and 50 ms in air. The submerged click train shown contains 17 identifiable clicks (the other submerged signatures varied in length from 4 to 27 clicks). A representative click selected from the submerged train is nearly monochromatic, peaking at 290 Hz with a bandwidth of 30 Hz. A representative click from the in-air rookery vocalization, on the other hand, involves both a 325 Hz fundamental frequency and a 650 Hz harmonic. The rookery call is consistent with open-mouthed threat calls by males (Le Boeuf and Peterson, 1969; Le Boeuf and Petrinovich, 1974).

No similar click train signatures could be found in the data beyond these two dives of subject ES95-1. Additional signatures may have been absent, buried in flow noise, missed by the recording schedule, or overlooked by the signal detection method used (visually inspecting spectrographic records). Indeed, the two weak click trains were only discovered by listening carefully to the record that contained the stronger ones, and their presence could only be confirmed by cross-correlating with a single click taken from one of the stronger signatures.

The repeatability of the signatures across a 90 min period and the lack of observed reverberation suggests local or nearby origin. Creaking of the instrument package may have caused the sounds, although if this were the case one would expect it throughout the deployment. The submerged signature's lower click frequency and longer click interval would not be inconsistent with elephant seal vocalization in a denser medium, although production of a modified male threat call by an apneic juvenile female would be unusual.

The two weak click trains were unlikely to have been echoes of the stronger trains. The weak trains occurred together in the same 10 s period and were separated by more than a minute from the stronger trains occurring before and after. The weaker signatures, and indeed all the signatures, may have originated from a following source rather than from the tagged subject. One possible source could be a male conspecific harassing the female subject, although we found no evidence of subject response. Alternately, the combination of strong and weak signatures may reflect a variable subject source level or perhaps an interaction between the subject and a conspecific. If the subject emitted the stronger signals and a conspecific produced the weaker signals with similar source characteristics, the 17 dB difference in received levels would indicate a propagation distance of 5–10 m.

5. Concluding remarks

Our results demonstrate that hydrophone tags can assess subjects' production and reception of low-frequency sound, measure potential interference from anthropogenic sources, and detect basic behavioral responses. Moreover, we find that the tags can acoustically measure swim stroke, respiration, and cardiac function, and can even obtain position information from ranging beacons. Flow noise obscured signals of interest far less than we feared, as the seals often swam slowly enough to allow detection of relatively faint sounds. At such times flow noise fell 10–30 dB below the

worst-case levels (Fig. 4), not infrequently falling below 75 dB re $1 \mu\text{Pa}^2/\text{Hz}$. Many potential acoustic stimuli arrived well above this noise floor, such as RAFOS (Fig. 5), ATOC (Fig. 6), and vessel noise (Fig. 8). While flow noise measured by the CAP could inhibit our detection of these sounds, natural flow noise experienced at a subject's ears could have a similar effect on the subject. The strength of naturally experienced flow noise and the extent to which it affects the hearing thresholds of swimming elephant seals remains unknown.

Researchers investigating the behavior of wild animals must be concerned about the potential effects their observation methods may have upon their subjects' behavior. Direct visual observation at sea usually relies upon vessels or aircraft, which have been demonstrated to disturb marine mammals under certain circumstances (Richardson et al., 1995). Archival tags eliminate the need to follow a subject closely, but tagging may also affect subject behavior, and a tagged subject may not resume normal behavior immediately after release. The flexibility of a programmable tag could allow it to postpone sampling until normal behavior resumes, either by waiting a specified period or by monitoring the behavior itself for a return to baseline.

The behavior of the CAP subjects may have been influenced by the CAP's unusual bulk and weight relative to other tags commonly used on elephant seals. This possibility can be tested, when a sufficient sample set exists, by comparing dive patterns observed by the CAP to those observed by much smaller time-depth recorders. Use of the CAP with most other marine species will require reduced size and weight. We expect the continued miniaturization of solid-state mass storage to enable such improvements; for example, if solid-state memory replaces the hard disk, then a lightweight resin package may substitute for the large and heavy pressure housing.

Elephant seals are highly vocal on land, but they have not been known to vocalize underwater. Biologists have listened for underwater vocalizations of elephant seals in shallow waters near their haul-out sites, but except for one unsubstantiated report (Poulter, 1968), none have been identified. The only putative vocalizations we have detected in our acoustic records of seals at sea are the 7 strong and 2 weak low-frequency click trains reported in this paper. While these sounds resemble those used by males for communication in air, the function of producing them underwater is unclear. The weak signatures among the strong ones, or possibly all the signatures, may represent communication from another seal nearby; however, no other evidence exists that elephant seals interact or travel together when at sea. The sounds' occurrence during the "drifting" portion of drift dives (Le Boeuf et al., 1992; Crocker et al., 1997) may suggest a relation to dive behavior. Perhaps the click trains represent an attempt at depth sounding using echoes from the seafloor; however, the fainter click trains just discussed did not have the strength or timing to have been echoes from louder clicks produced earlier by the same seal. The issue of echolocation in pinnipeds has a dubious history, with reports of echolocation in captive animals (e.g. Poulter, 1963, 1966; Renouf et al., 1980; Renouf and Davis, 1982) being questioned by other researchers (Schusterman, 1967; Schusterman et al., 1967; Oliver, 1978; Wartzok et al., 1984). It is uncertain that the click trains represent vocalizations produced by the subject or a conspecific, and these results should not be interpreted as suggesting

either echolocation or underwater communication in elephant seals. The determination whether animals use low-frequency sound for echolocation or communicative exchanges will require hydrophone tag recordings with sufficient dynamic range and sensitivity to detect echoes or vocal responses. Nevertheless, these results highlight the potential of CAP technology to quantify and place in context the vocalization behavior of specific individuals in their natural setting. In particular, statistical knowledge of individual vocalization behavior obtained with CAPs or other hydrophone tags could provide the “ground truth” necessary to more accurately census vocalizing marine mammals using acoustic techniques.

The experiments reported here utilized a translocation paradigm involving subjects that returned more or less directly to their rookery from the release site (Le Boeuf, 1994; Oliver et al., 1998), an approach which allowed relatively continuous acoustic sampling. Longer deployments during natural seal migrations, which took place in early 1997 and are planned for 1998, can take greater advantage of the sampling and storage flexibility of the CAP design. Depending on research goals, one might record either deep periods when the seal was swimming slowly (low noise, high probability of detecting distant low frequency signals), occasional whole dives, or synoptic windows during specified times or circumstances. Data compression and larger capacity disks, with the former possibly executed in hardware to save power, could improve data capacity over the translocation configuration by a factor of 5 or more. The resulting 120 h of acoustic storage at a 2 kHz sampling rate would permit 3% of a 6 month migration to be recorded.

RAFOS signals may be useful for determining the location of deep-diving or dwelling marine animals compared with other techniques. Satellite and radio tracking require subjects to break the surface regularly. Light sensor tags can estimate longitude for shallow-water animals without their surfacing, but provide less reliable estimates of latitude (Wilson et al., 1992). Deep-water animals may be tracked from research vessels using acoustic transponder tags (e.g. Watkins et al., 1993), but only for short periods and at significant expense. Hydrophone tags deployed in conjunction with RAFOS experiments may overcome these problems. Although we only detected one RAFOS signal out of 25 periods examined for translocated seals, we expect a higher detection rate for deeper-diving migrating seals located away from coastal bathymetry. On the other hand, the maximum of only two RAFOS position fixes per day all but rules out RAFOS as a means of assessing response to sudden or localized stimuli.

The CAP has demonstrated the capability to measure a suite of potential behavioral and physiological response indicators, including depth, stroke rate, cardiac function, and respiration. Depending on the usefulness of these indicators from species to species, hydrophone tags will improve our ability to study the responses of free-ranging marine animals to their environment. Diving and movement patterns can indicate disturbance reactions to noise by marine mammals (Richardson et al., 1995). Heart rate often serves to gauge the response of terrestrial animals (e.g. MacArthur et al., 1979), but for diving animals it varies dramatically with dive cycle and its interpretation as a disturbance measure requires further research. For example, Fedak et al. (1988) noted an elevated heart rate associated with aggression in one

free-ranging harbor seal (*Phoca vitulina*), but observed depressed heart rates in frightened captive grey seals (*Halichoerus grypus*).

Finally, hydrophone tags address serious obstacles to the study of underwater social communication. Understanding a communication requires identification of the vocalizing animal and knowledge of its audience's response, both difficult in the marine environment. Even when an observer can directly assess vocalizations and visual displays, the unbiased methods of sampling behavior required for accurate interpretation (Altmann, 1974) have remained difficult to implement underwater. Hydrophone tags such as the CAP may resolve these problems. These tags can identify a vocalizing animal (Tyack, 1991; Tyack and Recchia, 1991), and, for the receiving animal, can simultaneously monitor acoustic stimuli, behavior, and physiological response.

Our results suggest that CAP technology may increase our knowledge of animal behavior and physiology in the wild, while decreasing the logistic constraints, costs, and potential disruption associated with study vessels. Hydrophone tagging appears to offer a valuable new observational tool for the study of free-ranging marine animals.

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