TECHNICAL NOTE

Including Whale Call Detection in Standard Ocean Measurements: Application of Acoustic Seagliders

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ABSTRACT

Over the past decade, fixed recorders have come into increasing use for long-term sampling of whale calls in remote ocean regions. Concurrently, the development of several types of autonomous underwater vehicles has demonstrated measurement capabilities that promise to revolutionize ocean science. These two lines of technical development were merged with the addition of broadband (5 Hz to 30 kHz) omni-directional hydrophones to seagliders. In August 2006, the capability of three Acoustic Seagliders (ASGs) to detect whale calls was tested in an experiment offshore Monterey, California. In total, 401 dives were completed and over 107 hours of acoustic data recorded. Blue whale calls were detected on all but two of the 76 dives where acoustic data were analyzed in detail, while humpback and sperm whale calls were detected on roughly 20% of those dives. Various whistles, clicks and burst calls, similar to those produced by dolphins and small whales, were also detected, suggesting that the capability of ASGs can be expanded to sample a broad range of marine mammal species. The potential to include whale call detection in the suite of standard oceanographic measures is unprecedented and provides a foundation for mobile sampling strategies at scales that better match the vertical and horizontal movements of the whales themselves. This capability opens new doors for investigation of cetacean habitats and their role in marine ecosystems, as envisioned in future ocean observing systems.

Introduction

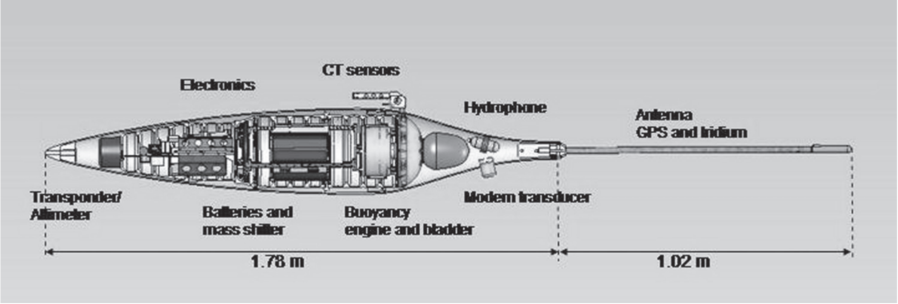
Over the past decade, detection of calls on fixed recorders deployed in remote regions of the world ocean has provided startling new perspectives on the seasonal occurrence of large whales (e.g., Moore et al., 2006; Mellinger et al., 2007). Multi-year records of blue whale (*Balaenoptera musculus*) calls are now documented from ten ocean regions including the Gulf of Alaska (Stafford, 2003), North Pacific (Watkins et al., 2000; Stafford et al., 2001), Eastern Tropical Pacific (Stafford et al., 1999), Northern mid-Atlantic (Nieukirk et al., 2004), Northeast Atlantic (Mellinger and Clark, 2003), Antarctic Peninsula (Širović et al., 2004), Scotia Sea (Širović et al., 2006), Indian Ocean (Stafford et al., 2004), eastern Antarctic coast, and southern Australian waters (Gedamke et al., 2007). Blue whale calls are arguably the 'best' signal for long-range detection, due to their low frequency (16-100 Hz), long duration (20-100s) and loudness (50 W or 188 dB re 1µPa at 1 m), but calls of other species including fin, humpback, right and sperm whales were also recorded at many of these locations. Unfortunately, concomitant oceanographic measurements are often lacking in these studies, although such measures are essential to investigations of cetacean habitat selection and their role in marine ecosystems. Without a suite of standard oceanographic measurements (e.g., temperature, conductivity, optical backscatter, dissolved oxygen, chlorophyll) to complement the whale call detections, researchers are left to search for environmental records from nearby moorings or satellite images that best match the recorder deployments. This method often results in comparatively crude depictions of whale habitat features (e.g., Moore et al., 2002), and hampers efforts to include whales in predictive models of marine ecosystems.

The development of several types of autonomous underwater vehicles over the past decade promises to revolutionize ocean science (Howe and Miller, 2004; Bellingham and Rajan, 2007). One such platform, the Seaglider (Figure 1a), engineered at the University of Washington (UW) with support from the Office of Naval Research (ONR) and the National Science Foundation (NSF), is a small (2.8 m) autonomous underwater vehicle designed to dive from the ocean surface to a programmed depth while measuring a standard suite of oceanographic parameters (Eriksen et al., 2001; Rudnick et al., 2004). Seagliders are low power, comparatively quiet and capable of multiple dives to 1,000 m over distances of tens to thousands of kilometers. The glider is propelled by buoyancy force (a pump moves oil between internal and external rubber bladders, changing the volume and thus the density), while vehicle direction is controlled by shifting the battery pack fore and aft and side to side. Wings provide hydrodynamic lift to propel the vehicle forward as it sinks or rises, at speeds up to 0.7 knots (Eriksen, 2001). Global Positioning System (GPS) and Iridium units provide navigation and communication capability whenever the units surface.

In 2005, Seagliders deployed in the North Pacific and the Labrador Sea set duration (191 days), distance (over 3,000 km), and dive records (over 600 dives; Mercer et al., 2007). This endurance spurred plans for broader application of these platforms to oceanographic investigations. The capacity to produce, detect, and record underwater sounds seemed a logical next step in Seaglider development and one that could link whale call detection capabilities developed for fixed recorders to mobile platforms. So, in 2006, two acoustic subsystems were added to three Seagliders, which subsequently went to sea in trials near

FIGURE 1

Acoustic Seaglider (ASG) deployment during the PLUSNet MB06 experiment (a) and internal assembly display (b).



Monterey Bay, California. The ability of these platforms to simultaneously record oceanographic data and whale calls while completing a series of operational dives was demonstrated and is provisionally reported here.

Methods

Seaglider Modifications

Three Seagliders became 'Acoustic Seagliders' (ASGs) with the addition of broadband (5 Hz to 30 kHz) omni-directional hydrophones in the tail cone (Figure 1b). One of the gliders was also fitted with a modem subsystem to provide two-way underwater communications capability, as described in Howe (2006). The modem frequency band was 23-27 kHz and, as this glider transmitted very infrequently, specifics as to this aspect of performance are not discussed further here. Each broadband hydrophone was connected to a low-power processor (CF2) and coupled to a flash memory (4 Gbyte) and a low-temperature hard disk (60 Gbyte) for long-term data storage. This onboard processing and storage allowed the acoustic data to be digitized with 120 dB of dynamic range (over two gain channels) with a system noise level floor of 34 dB re 1μPa/(Hz)$^{1/2}$.

Experimental Procedures

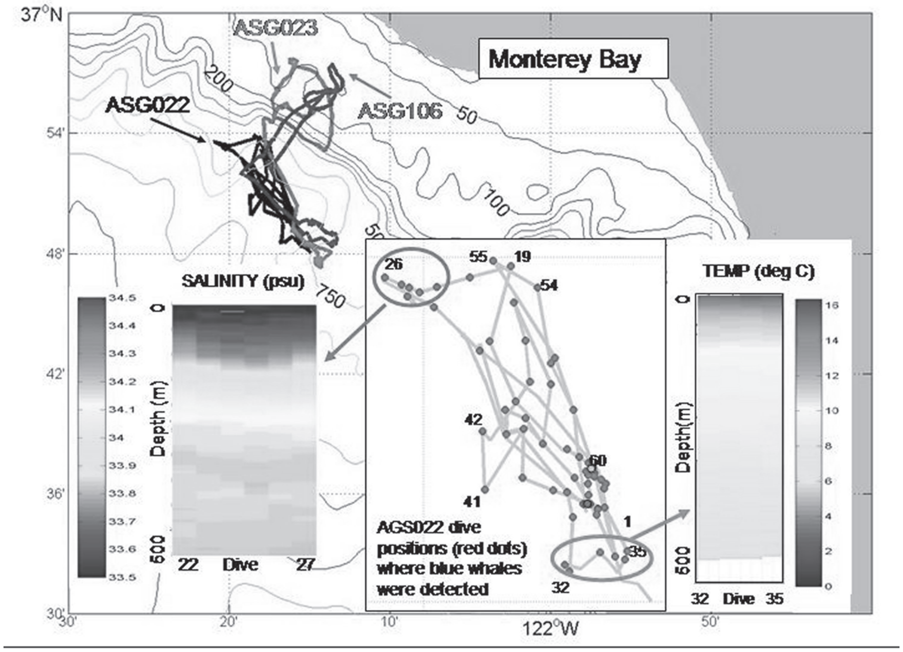
The three ASGs were deployed just northwest of Monterey Bay, California, from 12-23 August 2006, as part of the ONR PLUSNet MB06 experiment. Two gliders (ASG 022 and 023) sampled at 5 kHz, while the modem-instrumented glider (ASG 106) sampled at a rate up to 64 kHz with low pass filtering at 30 kHz. Power spectra were calculated *in situ* for a small subset of the data and telemetered back to shore with the other oceanographic data when the glider surfaced; in the future the results of more sophisticated *in situ* processing can be available in near-real time to support other contemporaneous activities.

Results

In total, 401 dives were completed and over 107 hours of data recorded, with deployments in both shallow continental shelf (50-200m) and deep slope-basin (200-900m) habitats offshore central California (Figure 2). Continuous acoustic recording typically lasted 10–20 minutes, followed by a short pause (3–5 minutes) while the glider was on the surface, then another recording period. Other mission requirements prevented more continuous data collection. Significant glider self noise was limited to the brief periods when the buoyancy pump was running, typically at dive apogee, or the even shorter

FIGURE 2

Track of three ASG deployments northwest of Monterey Bay. Inset details track of ASG 022, with dots depicting locations where loud blue whale calls were received. Example salinity and temperature panels given for two dot-cluster locations at track boundary.



periods when the roll or pitch motors were running. Overall, on a dive lasting an hour, < 5 minutes of acoustic data were contaminated with self noise. Over 80% of the acoustic sample (86h) was recorded on ASG 022 during the first nine days of the experiment. An additional 10h of acoustic data were recorded on ASG 023, with 11.5h of recording on ASG 106 divided between sampling at 5 kHz (2.5h) and 64 kHz (8.9h).

TABLE 1

Number of dives when calls of four whale species were identified on two ASGs during the experiment offshore Monterey Bay, California, August 2006.
E = occurrence of echolocation click series

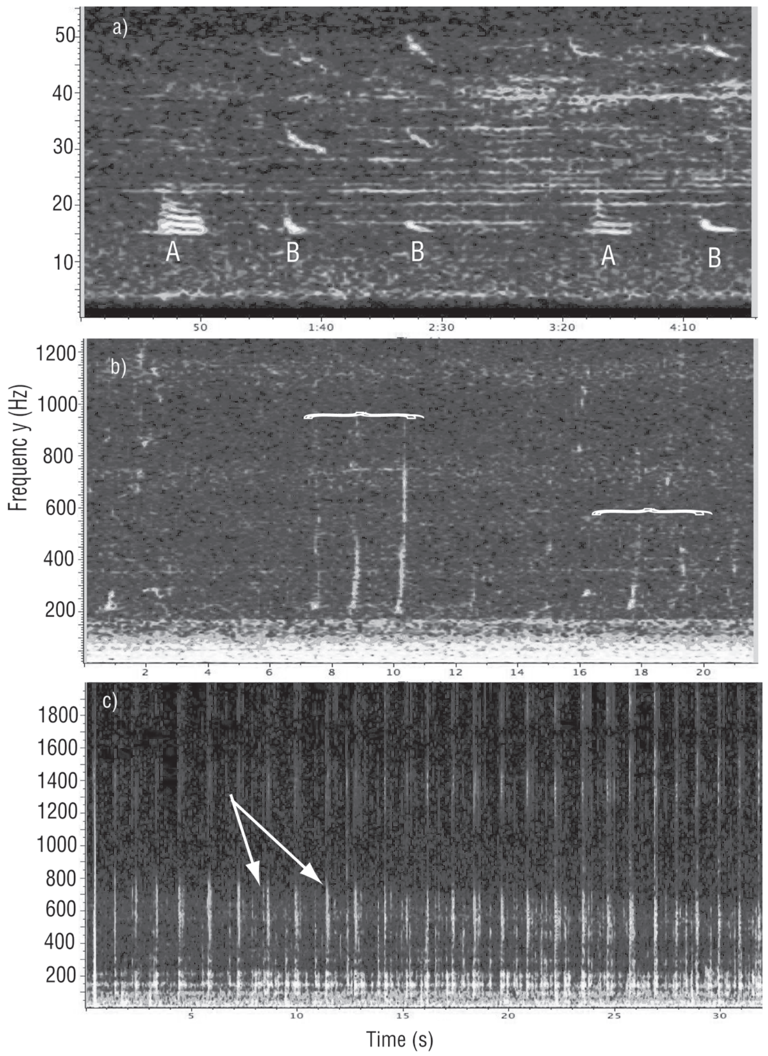
Platform	No. Dives	Blue Whale (# calls)	Humpback Whale	Sperm Whale	Killer Whale*	Unknown Odontocete (E)
ASG 022	60	58 (904)	12	16	2	16 (9)
ASG 023	16	16 (49)	3	1	0	0

* provisional ID, due to very low signal/noise

Acoustic data from 76 dives completed by ASG 022 (60 dives) and ASG 023 (16 dives) were downloaded and analyzed with the aid of species-specific call detectors, developed using ISHMAEL (Mellinger, 2001) and by visual and aural examination of spectrograms. Both gliders recorded calls from blue, humpback, and sperm whales, as evidenced by species' diagnostic calls (Table 1; Figure 3). Blue whale calls were detected on all but two of the 76 dives, with a total of 953 individual calls counted. Humpback whale calls were detected on roughly 20% of dives conducted by each ASG, while sperm whale calls were far more prevalent on the ASG 022 dives (27%) than on ASG 023 dives (6%). This difference is likely attributable to the greater number of ASG 022 dives conducted seaward of the shelf break where deep-diving sperm whales are more common.

FIGURE 3

Example of (a) blue, (b) humpback and (c) sperm whale calls recorded on ASGs. Diagnostic features include the A-B-B sequences produced by blue whales in the eastern North Pacific, distinctive triplet upglides of humpback whales (bracket) and the broadband clicks of sperm whales (arrows). Note: frequency/time axes vary by species.



Some calls could not be positively attributed to species (Table 1). Signals that appeared to be killer whale calls were detected twice on one of the ASG 022 dives, but these were very faint. On sixteen ASG 022 dives, various whistle, clicks, and burst calls, similar to those produced by dolphins or small whales, were detected, with echolocation clicks noted on 9 of the 16 dives. Finally, sea lion barks and seabird calls were recorded on 15 and 9 occasions, respectively, on ASG 022; and on one occasion each on ASG 023. These detections occurred at the beginning and ends of dives, when the gliders were close to the surface.

To demonstrate the capability of ASGs to integrate whale call detections with conventional oceanographic measures, loud blue whale calls (i.e., from nearby whales) were matched to ASG dive locations (Figure 2: inset track) and composite temperature and salinity panels derived to show the associated real-time hydrography. Not surprisingly, there was a clear temperature and salinity cline at roughly 130-200 m in the area where the blue whales were detected (Figure 2: inset hydrography). These results complement data from a long-term study of blue whales within Monterey Bay, wherein whales have been shown to forage on dense euphausiid aggregations that occur between 150-200 m along the edge of Monterey Bay Submarine Canyon (Croll et al., 2005).

Discussion

We are very encouraged by the results of this initial ASG experiment, in that blue, humpback, and sperm whale calls were prevalent in the data record. The detection of higher-frequency calls and echolocation clicks associated with smaller whales and dolphins suggests that with additional engineering, ASGs will be able to routinely detect signals from a broad suite of marine mammal species. Moreover, we were surprised to note that sea lions and seabird calls were heard when the ASGs were near the surface. Overall, this experiment demonstrates that, with refinement of marine mammal call classification tools anticipated via ongoing efforts such as the PAMGUARD program (http://www.pamguard.org) and others, the routine inclusion of marine mammal calls as a standard ocean metric is within our technical grasp.

The capability of the ASGs to include whale calls as an oceanographic metric compiled with standard temperature and conductivity measures provides unprecedented opportunities to develop mobile sampling strategies for these top-predators over varied temporal and spatial scales. Until now, passive acoustic sampling for marine mammals has been conducted via static deployments of fixed recorders, or by towing a cabled array behind ships conducting transect surveys (e.g., Barlow and Taylor, 2005). In both cases sampling is confined in space and time, often at scales that are mismatched to the natural history of the target species. Conversely, Seagliders are capable of sampling at vertical and horizontal scales similar to the diving and foraging movements of the whales themselves. For example, given reports of intensive blue whale feeding in Monterey Bay (Croll et al., 2005), foraging hotspots north and south of the bay (e.g., Oleson et al., 2007) and the results of our experiment, one can imagine that much more could be learned about the dynamics of blue whale movements and behavior from an array of ASGs sampling all along the California shelf break. Indeed, a suite of mobile and fixed sensors sampling across a range of ecological scales is exactly what is envisioned in most ocean observatory plans (e.g., Howe and Miller, 2004).

Future Applications and Partnerships

For many oceanographers, the question may be: why do this? Why sacrifice precious battery power for acoustic data acquisition, storage and processing for the identification of marine mammal calls? There are many possible answers to such a question, and we list three we think important here.

1) Understanding marine mammal ecology, the when, where and why in the life history of these ocean-going predators provides a framework for investigating ocean dynamics. Patterns of marine mammal distribution and movements reflect oceanographic variability, from local to basin scales—thus, these highly adapted animals can inform oceanographers of potentially overlooked ocean structure and lead to enhanced sampling protocols over the long term.

2) Development of acoustical oceanography requires underwater noise budgets that account for sound contribution from marine mammals calls, which can be seasonally significant (e.g., Curtis et al., 1999), as well as sounds from sonorous fishes (Rountree et al., 2006), earthquakes (Smith et al., 2004), wind and rain (Nystuen, 2001) and anthropogenic sources such as ships, sonars and geophysical surveys (Dahl et al., 2007). Quantification and integration of these sources to standard databases are fundamental to the type of acoustic sensing anticipated in future ocean observatories (Howe and Miller, 2004).

3) Future ocean resource assessment and management requires the type of fine-scale measurement and data availability that only autonomous mobile ocean sensors can provide. Seaglider trials in other ocean areas provide further evidence of their utility as a tool for investigation of baleen whale feeding ecology (e.g., Baumgartner et al., 2006) and for mitigation of naval training activities (e.g., Sanderson, 2007). Perhaps the most useful contribution of future ASG deployments is the potential, with development of species-specific signal detectors, to transmit the identity and location of animals in near real-time to users on shore or at sea. The need for timely and regional information about marine mammal distribution, abundance, and movements is bound to increase with expanded military, commercial, and recreational activities in the oceans.

Partnerships among academia, agencies, and advocacy organizations can foster development of ocean observing systems wherein ASGs can contribute. For example, we were fortunate to conduct the PLUSNet experiment in the vicinity of the long-term study site that scientists at the University of California, Santa Cruz (UCSC) maintain for blue whales in the upwelling system of Monterey Bay Canyon (Croll et al., 2005). Currently, the UCSC Center for Integrated Marine Technologies supports a nascent ocean observing system, including data fields from HF radar, moorings, ship surveys, remote sensing, bioacoustics, and apex predator tagging (http://cimt.ucsc.edu/bioaccoustics.htm). Our results demonstrate the capability of ASGs to add to this suite of data, which anticipates the type of data streams planned for the NSF ocean observatories program ORION and the Integrated Ocean Observing System. Integration of passive acoustic sensors in Seagliders augment sampling in both space and time, providing the backbone of information required as we enter a new era of ocean exploration.

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