Engineering tools for studying marine mammals

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Introduction

Whales and dolphins (cetaceans) can be challenging to study because they often occupy areas that are remote and inhospitable, spend much of their lives underwater, and are diverse in their behaviors and habitats. Traditional methods for studying marine mammals in the ocean are conducted by ship-based visual observations in which animals are counted and behaviors are noted. However, whales and dolphins spend as much as 95% of their time below the sea surface beyond visual range providing traditional methods sparse data with which to base ecological and behavioral models. On the other hand, these animals often use sound while submerged to sense their environment, to communicate with each other, and to find food by echolocating allowing acoustic monitoring methods to provide rich data sets for studying cetaceans.

Because marine mammals are so reliant on sound for their life functions, they can be highly susceptible to acoustic disturbances. For example, tactical Navy sonar use has been related to marine mammal mass strandings (Frantzis, 1996; Cox et al., 2006) and increased ambient noise levels have been attributed to large-scale commercial shipping (McDonald et al., 2006) potentially reducing marine mammal acoustic capabilities to locate food and mates. These adverse effects to anthropogenic activities, especially the response to sonar, have fostered the development of technologically advanced tools for studying marine mammals.

There are two main types of tools for studying the natural behavior of whales and dolphins and their responses to sound beneath the sea surface: tags and passive acoustic monitoring. Tags are small instrumented devices that are attached to individual animals and provide detailed behavioral information of the tagged animal. Because of the difficulty of finding animals in the ocean and attaching tags to them, not all species of marine mammals have been tagged and the number of tagged animals is relatively small, nevertheless, the detailed information tags have provided has greatly advanced our understanding of many species. Acoustic monitoring, while incorporated into some tag devices, is typically employed over much longer periods and over larger distances to provide temporal and spatial patterns of animal and anthropogenic sounds on which to base ecological and behavioral response models. In this paper, I summarize the technologically advanced devices used for tagging and acoustic monitoring methods, and discuss some of the challenges of making measurements with these types of tools in the ocean environment.

Tags

Tags for studying whales and dolphins are available with various capabilities. These capabilities include pressure sensors for measuring depth, global positioning system (GPS) and Argos satellites receivers for large scale movement tracking, compass sensors for heading, multi-axis accelerometers for swimming dynamics, acoustic sensors for recording sound, and video for capturing images (e.g., Andrews et al, 2005; Hooker and Baird, 1999; Marshall, 1998; Johnson and Tyack, 2003). There are two main attachment techniques for these tags: long-duration (weeks to months) tags use barbed darts that pierce the animal's skin and are deployed using a crossbow or air-gun (Figure 1A, Andrews et al, 2008), whereas, short-duration (hours to days) tags use non-invasive suction cups for attachment and typically are placed on an animal using long poles (Figure 1B, Burgess et al, 1998; Goldbogen et al, 2005).

Typically, tracking tags use barbed darts to provide long deployments and can be packaged in a small form factor since they send their data (locations) to scientists through satellite communications and are not recovered. On the other hand, recoverable tags use short-duration suction cups but require larger packaging for data storage, additional sensors and batteries, radio transmitter and flotation. Acoustic recorders have been incorporate into these multi-sensor, short-duration tags and have provided valuable information on the acoustic behavior of large cetaceans (whales) thus far, but they have not been used on smaller cetaceans (dolphins) as the size of these tags would have noticeable weight and hydrodynamic drag that would interfere with smaller animals' movements. Additionally, small cetaceans produce high frequency (10's – 100's kHz) sounds compared to larger, lower frequency whales (10 Hz – 1000's Hz), so faster sample rates are needed for smaller animals, which leads to larger data storage and larger battery capacity. Fortunately, loss-less data compression can be employed and data storage devices continue to become smaller, lower power, and higher capacity as the consumer electronics industry continues to advance. The current best example is a DTAG which is based on cell phone technology and can record compressed loss-less audio up to 192 kHz along with pitch, roll, heading, and depth (Johnson and Tyack, 2003), but has not been used on animals smaller than about 5m. So, the current challenge is to further miniaturize the packaging of these electronics in a container that keeps the seawater out at high pressures, has buoyancy and a radio transmitter for recovery, and is small enough to be attached to dolphins without affecting their swimming behavior.

Passive Acoustic Monitoring Tools

There are a variety of tools used to remotely monitor free-ranging dolphins and whales using passive acoustics over long periods. Some provide real-time acoustics via cabled or radio-linked hydrophones (e.g. McDonald 2004), while other systems are autonomous and record sounds internally (e.g. Fox et al, 2001; Clark et al, 2002; Wiggins, 2003; Lammers et al, 2008). In many cases, these autonomous acoustic recorders are more practical than real-time systems because they can be deployed in various remote locations worldwide, have lower costs, and collect data without personnel supervision. Unlike acoustic tags, autonomous recorders have larger data and power storage capacities which allow them to monitor for longer periods (months – year). Autonomous acoustic recorders also can be distributed over large areas to provide temporal and spatial patterns and relative abundance estimations of calling animals (e.g. Sirovic et al, 2004; Oleson et al, 2007; Munger et al, 2008), and they can be configured into arrays with close sensor spacing for tracking individuals or groups of animals (e.g. McDonald et al, 1995; Tiemann et al, 2004; Frazier et al, 2009).

One of the most capable autonomous systems currently available is a High-frequency Acoustic Recording Package (HARP) which samples up to 200 kHz and has 2 TB of data storage on 16 laptop type disk drives (Figure 2) (Wiggins and Hildebrand, 2007). I have been developing HARPs since 2004 at Scripps Institution of Oceanography and deploying them worldwide in deep and shallow waters to monitor and track a variety of marine mammals from low frequency (10 Hz) blue whale sounds up to high frequency (100 kHz) dolphin echolocation clicks. Sampling continuously at 200 kHz and 16-bits per sample fills up a HARP's disk space in about two months (~ 35 GB/day) requiring instrument recovery and refurbishment with new batteries and disks. However, servicing instruments every couple of months is expensive in terms of ship and personnel costs. One solution my group currently is working on is to increase data storage capacity while lowering power consumption by replacing the hard disk drives with solid state memory (NAND flash) as this type of data storage continues to decrease in price with increasing capacity.

Even as improvements are made to HARPs for longer deployments, our greatest challenge is analyzing the large amount of acoustic data collected by these instruments. Each instrument records up to 12 TB/yr and the number of instruments is continuing to grow from our current count of 25 (i.e., 300 TB/yr). Acoustic data are measured as time series of pressure which then can be transformed into the spectral (frequency) domain via Fourier transforms and displayed as spectrogram (time-frequency) plots. Spectrograms are often used to evaluate acoustic data for animal and anthropogenic sounds because most species and man-made sounds are unique in spectral and temporal character and can be easily differentiated (Figure 3A). However, evaluating wide frequency band data, such as from HARPs, can be conducted by an analyst only near real-time because of human and computational limitations, prohibiting analysis of complete data sets directly using spectrograms. As an efficient alternative, Long-Term Spectral Averages (LTSAs) can be computed and used to provide an overall view of a large data set along with providing a means to search for and evaluate events of interest (Figure 3B) (Wiggins and Hildebrand, 2007). LTSAs are essentially spectrograms with each time pixel representing many (1000’s) spectra (eg. 5 sec) instead of just one (eg. 5 msec as with spectrograms).

For a more detailed and quantitative analysis, automated detectors can be used on time series, spectrograms and LTSAs to find specific sounds with known characteristics in large data sets. The resulting detections can be organized by time and location to reveal seasonal, daily, and regional patterns related to species behavior and habitat. A detection algorithm’s performance is based on various algorithm parameters and the data set. Once an algorithm’s parameters have been optimized through multiple training tests conducted by analysts, it can be used in an automated way on a full data set to find sounds with specific characteristics. However, since these long-term data sets have a wide range of sounds, many detection algorithms must be developed, optimized and then applied to the same large data sets. In the future, our approach to this problem of running multiple detectors on large data sets will be to employ multiple processors arranged in clusters that can access the same data near-simultaneously. Using multiple processors in this way will allow for efficient detections of a wide range of animal and anthropogenic sounds.

Summary

Whales and dolphins use a variety of sounds underwater to sense their environment and to communicate. These sounds can be recorded over long durations using passive acoustic monitoring instrumentation and over shorter periods for more detailed information with devices attached directly to animals. While solving some of the challenges of developing these tools has provided information on marine mammal spatial and temporal distribution and acoustic behavior, and potentially their response to anthropogenic sound sources such as sonar and explosions, these technically advanced tools also have created another challenge in analyzing the large data sets generated.

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Figure Captions

Figure 1. Two types of tags, their attachment methods, and results. A) Long duration (days to months) barbed darts on satellite tracking tag, air-gun deployment of tag on killer whale, and one month of killer whale tracks (figures 1-3 in Andrews et al, 2008). B) Short duration (hours to days) suction cups on B-probe (acoustic, depth, 3-axis acceleration tag), tag attachment on blue whale using pole, and 2 hour dive profiles from a tagged fin whale offshore of southern California (photos Erin Oleson; Burgess et al, 1998; Goldbogen et al, 2006).

Figure 2. High frequency Acoustic Recording Package (HARP). A) Data logger attached to end cap of pressure resistant case. The autonomous data logger consists of low-power electronics including 200 kSample/sec analog-to-digital converter, low drift (10^{-8}) clock, and about 2 TB of data storage on 16 laptop-style hard disk drives. B) HARP instrumentation packaging in a seafloor-mounted frame (Wiggins and Hildebrand, 2007).

Figure 3. Example HARP acoustic data offshore of southern California. A) Five second spectrogram shows dolphin clicks from about 25 kHz up to 100 kHz, dolphin whistles from about 8 kHz to over 20 kHz, and man-made sonar around 3 kHz. B) Long-Term Spectral Average (LTSA) over 1-1/4 hours shows a bout of dolphin whistles and click and sonar. Figure 4A is taken from approximately the time corresponding to 0.5 hours.