PAPER

Autonomous Acoustic Recording Packages (ARPs) for Long-Term Monitoring of Whale Sounds

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ABSTRACT

Advancements in low-power and high-data capacity computer technology during the past decade have been adapted to autonomously record acoustic data from vocalizing whales over long time periods. Acoustic monitoring of whales has advantages over traditional visual surveys including greater detection ranges, continuous long-term monitoring in remote locations and in various weather conditions, and lower cost. An autonomous acoustic recording package (ARP) is described that uses a tethered hydrophone above a seafloor-mounted instrument frame. ARPs have been deployed to record baleen whale sounds in the Bering Sea, off the coast of southern California, near the West Antarctic Peninsula, and near Hawaii. ARP data have provided new information on the seasonal presence, abundance, call character, and patterns of vocalizing whales. Current development is underway for a broader-band, higher-data capacity system capable of recording odontocete whales, dolphins, and porpoises for long time periods.

INTRODUCTION

Monitoring worldwide whale migrations and regional populations is important for better conservation and management of these animals (National Marine Fisheries Service, 1998). The advancement of computer technology has made acoustic monitoring a cost-effective approach for studying acoustically active whale species. Low-power data acquisition systems and large-capacity data storage disks have allowed for continuous, long-term, acoustic recordings of whale vocalizations to be made by autonomous instruments. Furthermore, acoustic whale monitoring has an advantage over visual surveys because acoustic detection ranges are generally greater, whales may spend more time at depth calling than at the surface breathing, and autonomous acoustic monitoring can be conducted in all weather conditions, day and night, and in remote locations. However, visual surveys are still needed for detailed behavioral studies and species confirmation for lesser known or sparsely calling whales. Combining visual and acoustic surveys provides a powerful tool for studying whale abundance and ecology.

In March 2000, design and development of an autonomous acoustic recording package (ARP) to record baleen whale calls was initiated. An autonomous recording package approach has the advantage over real-time monitored systems because of its lower installation and personnel costs. Autonomous instruments can be deployed for long time periods (up to one year) in remote locations. Computer software can be used to detect calls automatically by scanning the acoustic data after instrument recovery. An ARP consists of a frame that rests on the seafloor and a hydrophone tethered above the frame (Figures 1 and 2). The frame contains the buoyancy needed for recovery, ballast weights for deployment, and pressure cases for batteries and ballast release and data logger electronics. ARPs have been configured to record up to 1 kHz sample rate continuously for more than one year. At these sample rates, calling baleen whales are recorded, but not higher-frequency-calling odontocetes (toothed whales). By June 2000, four months after project initiation, an ARP had been deployed and recorded its first baleen whale call. Since then, 25 ARPs have been fabricated and deployed in both shallow and deep water at a variety of locations including: the Bering Sea off the coast of Alaska, near San Clemente Island off the southern California coast, off the West Antarctic Peninsula in the Southern Ocean, and south of the Big Island, Hawaii (Table 1).

Many baleen whale calls are loud, low-frequency tones or narrow band sweeps that can be recorded with ARPs for seasonal distribution pattern studies (e.g., Richardson et al., 1995). For example, the fundamental frequency in northeastern Pacific blue whale B calls is around 18 Hz, lasts for about 20 s, and can have source power levels above 185 dB re 1 micro-Pascal (µPa) at 1 m (McDonald et al., 1995; Thompson et al., 1996; McDonald et al., 2001). Whale call acoustic time-series data are often transformed into frequency-based data using Fourier transforms so that the data may be viewed as spectrograms. Detecting calls in spectrograms is typically easier than with time-series representation, since the spectrogram helps to separate the narrow-band call from the broad-band noise. Analysis software programs were developed based on the high-level language development package, MATLAB®, because of its ease of use, rapid development time, portability, built-in toolbox functions (e.g., *Signal Processing Toolbox*), and graphical user interface capabilities. Also, development of automatic call detection and whale call tracking

Figure 1. Schematic of an autonomous acoustic recording package (ARP). The instrument package is deployed on the seafloor with a hydrophone suspended above it.

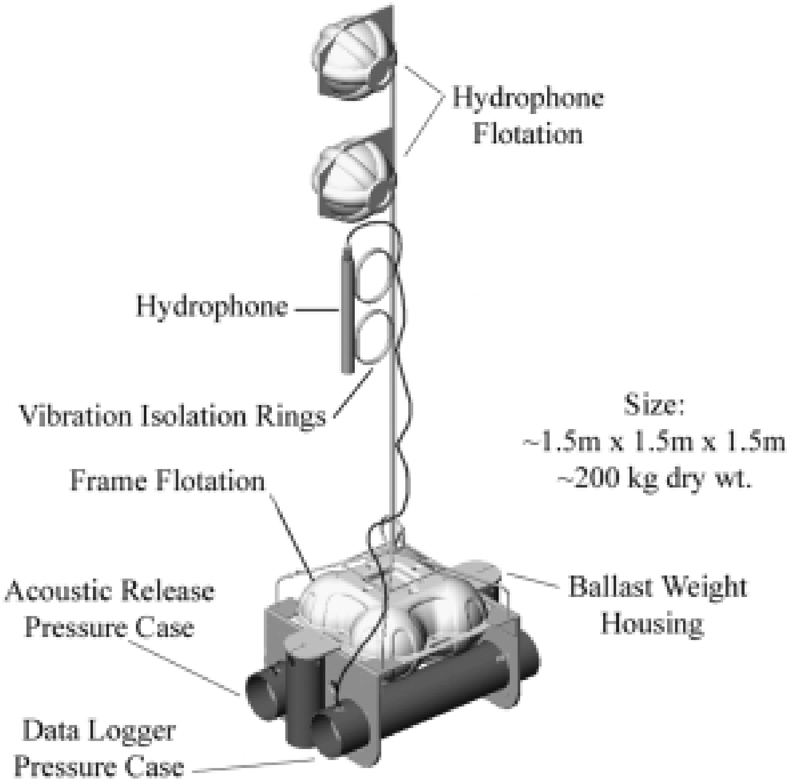


Figure 2. Photograph of an ARP ready for deployment. The hydrophone electrical cable and hydrophone are attached along a polypropylene line between the instrument package and the two hardhat glass spheres.

software is being conducted in collaboration with colleagues to aid in analysis of more than 60 GB of data per instrument per year (Mellinger, 2002; Tiemann et al., 2002).

Analysis of the first year of continuous data from Alaska, California, and Antarctica is revealing new information on the presence and abundance of calling whales. Some sites show seasonal occurrences of calling whales, while other sites have calling whales year-round. Diurnal calling patterns have been observed, and call/counter-call patterns detected.

METHODS

The key functional constraints of an autonomous acoustic recording system are low power and low acoustic and electronic self-noise. In addition, the functionality needed for baleen whale seasonality and abundance estimations is long-term deployments (up to one year) and moderate sample rates (up to 1 kHz). Additional constraints for this project were short development time and low cost. Rapid development required use of off-the-shelf components, tried-and-true methods and designs, and keeping the design and manufacturing processes simple.

Electronic Design

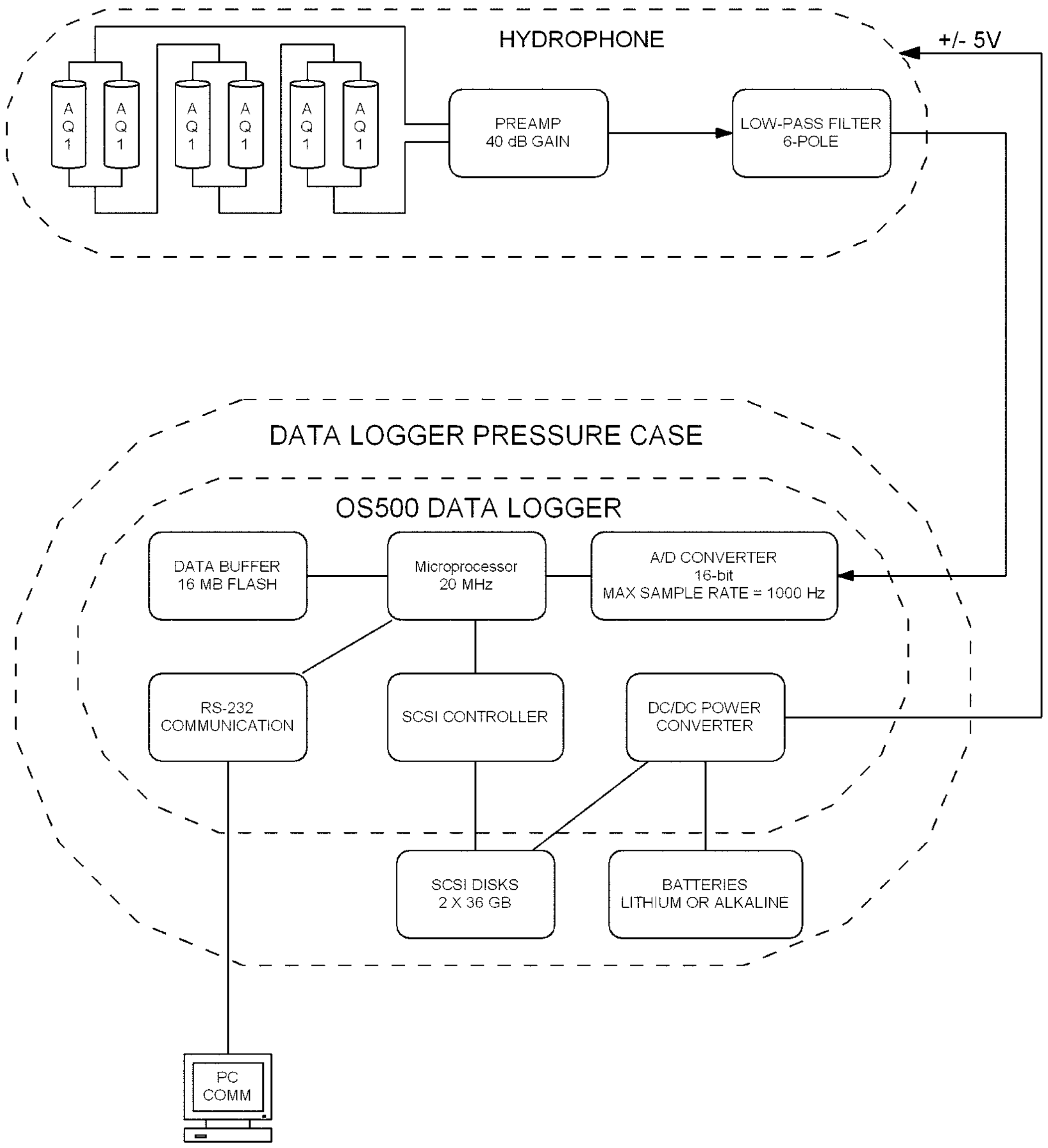
The first component considered in the ARP design was the data acquisition system because it is the primary power consumer. The electronic system's power consumption and deployment duration drive the mechanical design because accommodations for batteries must be provided. Ocean Sensors OS500 data logger (http://www.oceansensors.com/) developed by Dave Jacobs was used as an off-the-shelf solution (Figure 3). The OS500 is capable of sampling up to 1 kHz on one channel. At that sample rate, the power consumption of the data logger and hydrophone is around 600 mW. More than one-year deployments (~400 days) are obtained from lithium battery packs with approximately 580 Ahr at 10 V for the data logger and 135 Ahr at 17 V for the disk drives. Separate battery packs were used to prevent noise "spikes" from being recorded in the data caused by disk drive start-ups. Shorter deployments (up to 150 days) are possible with lower-cost alkaline battery packs. Data are 16-bit samples and are recorded on two 36 GB SCSI (small computer system interface) hard disk drives for a maximum storage capacity of 72 GB. The electronics boards are 10 cm x 18 cm and fit within the footprint of the disk drives, which provide compact packaging of the complete data acquisition system.

Hydrophones were produced using Benthos (http://www.benthos.com/) AQ-1 PZT (lead-zircon-titanate) ceramic cartridges and custom designed signal conditioning preamp and anti-aliasing electronics. The hydrophones were arranged as three sets of ceramic elements in series with each set made up of two ceramic elements in parallel (Figure 3). This

Table 1. ARP deployment, data quantity recorded, and calls detected. The first ARP deployment was in June, 2000. Currently, ARPs are deployed near southern California, in the Bering Sea, in the Beaufort Sea, in the Gulf of Alaska, and various locations around the Antarctica continent.

Site	# ARP Deployments	Begin Recording	End Recording	# Gbytes Recorded	Species/Call Type	# Calls per Instrument-year
Southern California	53	6/2000	4/2003	552	Blue B	109,972
					Blue D	27,939
					Fin	465,929
Bering Sea	4	10/2000	5/2001	80	N. Pac. Right	3,569
Antarctica	14	3/2001	3/2003	420	Blue	21,559
Hawaii	1	12/2000	7/2001	20	Blue, Fin, Humpback	N/A
Total	72			1072		

Figure 3. Block diagram of ARP hydrophone and data logging electronics.



configuration provides a sensitivity of –193 dB re Volts root-mean-squared (VRMS)/µPa and a –3 dB low-end rolloff around 5 Hz. The string of six ceramic elements was placed in a 5 cm diameter oil-filled, 50 cm long flexible polyurethane tube. The length of the hydrophone allows for good coupling to low frequency sounds and helps minimize acoustic noise generated by fluid flow past the hydrophone. The signal conditioning preamp and anti-aliasing electronics were placed in the flexible tube near the ceramic elements to provide amplification and filtering near the sensors and to minimize electronic noise pickup. The preamp was a 3-stage, low-power field-effect transistor design with 40 dB of preamplifier gain, followed by a 6-pole low-pass filter (-6 dB point at 250 Hz or 500 Hz, depending on sample rate) on the same printed circuit board.

Mechanical Design

A seafloor instrument package design was pursued because water column moorings can be costly in deep water and difficult to deploy and recover in shallow or deep water. Also, the large volume of batteries needed for long-term deployments can be more easily packaged in seafloor instruments. With a bottom-mounted mooring, the bulk of the instrument package rests on the seafloor and the sensor (hydrophone) is tethered above the instrument package (Figure 1) away from acoustic noise generated by the instrument (disk drive spin-up and fluid flow). Floating the hydrophone above the instrument also puts the sensor closer to the sound source and at a place that is less likely to be acoustically shadowed by seafloor topography. The hydrophone is tethered 10 m above the seafloor and is connected to its support line via two flexible polyethylene rings to provide additional acoustic noise suppression. The rings de-couple the hydrophone from the support line, which may vibrate due to ocean currents.

Rapid design of the ARP instrument frame, pressure cases, and internal hardware was done with the 3D modeling software, SolidWorks (http://www.solidworks.com/). This allowed for exploring various design scenarios, and clearance/fit checking. Also, weight and buoyancy calculations were obtained easily. The primary material chosen for the frame was non-corrosive, high-density polyethylene (HDPE). HDPE is a good frame material choice because it is buoyant in seawater, durable, low cost, comes in various shapes, and can be easily machined. The lifting bail and fasteners material was originally stainless steel 316. This choice works well in the deep ocean, however, stainless steel corrosion can become a problem in shallow water (<200 meters below sea level (mbsl)). The bails and fasteners were converted to titanium because many whale monitoring sites are in shallow water. The pressure cases are either 7075-T6 or 6061-T6 aluminum extruded tubes, anodized and painted, and rated to ~7000 mbsl and ~4000 mbsl, respectively.

The ARP recovery system is based on glass sphere flotation and expendable ballast drop weights. Flotation is provided by four, 30 cm diameter McLane Research Labs (http://www.mclanelabs.com/) glass spheres in a single molded hardhat. The four-ball hardhat is attached to the frame beneath the lifting bail. Additional flotation is provided by two separate glass spheres attached to the top of the hydrophone support line. The ballast is two, cylindrical 26 kg steel drop weights held in place by stainless steel burnwires. The burnwires are activated by an EdgeTech (http://www.edgetech.com/) acoustic transponder release system. An acoustic command is sent from the support ship, which causes the release system to apply a voltage between the burnwires and a saltwater ground. About 10-20 minutes are required for the wires to corrode sufficiently to drop the ballast weights. The instrument then floats to the sea surface, and the support ship's crew retrieves the instrument from the water. Often, disk drives and batteries are replaced and the ARP is re-deployed to collect another long-duration (2 months – 1 year) data set.

Software

ARP data are recorded with 16-bits (96 dB) of dynamic range in 64-KB size blocks with a timing header at the beginning of each block. These blocks are buffered and then streamed to a non-file system SCSI disk. Data must be uploaded into structured files for analysis. To analyze the data, MATLAB® (http://www.mathworks.com/) is used for displaying and processing the data in various ways. Sounds from the data can be displayed, played, saved as wav files or printed to standard graphic file formats. MATLAB® was chosen because of its familiarity in the scientific community, its portability between different operating systems, and its relatively easy use/programming. The MATLAB® code developed for displaying ARP data as time series, spectra, or spectrograms, called *Triton*, is configured with graphical user interface (GUI) buttons, sliders, and fill-in boxes to allow easy viewing and data manipulation. *Triton* is designed to be 'expandable' so that new functions can be easily implemented.

The amount of data produced by the ARPs is a major challenge for those analyzing it. For example, at 1000 Hz sampling, 16-bit data are recorded at a rate of around 173 MB per day or 63 GB per year. For population estimation, counting each call manually is a time-consuming process. For example, it took an analyst two months to count approximately 20,000 blue B calls in two weeks of ARP data from the southern California site. Automatic detection algorithm software is an alternative approach. After calls have been detected, statistics can be applied to investigate the significance of the call detections and correlate these calls with visual observations.

After preliminary analysis of data quality with *Triton*, recorded call counts are estimated using an automated detection algorithm. To detect calls, the software program, *Ishmael* (Mellinger, 2002), is used to cross-correlate a reference call with the spectrogram data. The detection threshold is adjusted to optimize the automatic detector results. The tradeoff provided by varying the detection threshold is between the number of false (non-call) detections and the number of missed calls. Depending upon call type and analysis requirements, false detections or missed call rates may be kept as low as 1-2 percent. After the *Ishmael* call detection algorithm has been trained for a certain call type and data set, it is applied to the large- scale data set to provide estimates of detected calls.

Another method for estimating calling whale abundance from ARP data is long-term spectral averaging. Spectral averaging involves averaging long periods of spectral data and then searching for call energy in specific frequency bands (e.g., Thompson, 1965; Curtis et al., 1999). The amount of energy in the whale call frequency bands may be used as a proxy for estimating the number of calls produced during the averaged time period. Depending upon season and location, whale call energy may be more than 10-15 dB above ambient noise when averaged over time periods of days to weeks.

RESULTS

The large quantity of whale call data recorded by ARPs have provided information on seasonal calling trends as well as daily variation in calling activity for various whale species and locations. ARP deployment, data quantity recorded, and preliminary automated detected call estimates from four sites are shown in Table 1. The detected call estimate results are topics of other papers in progress, but are presented here to show the significance of ARP recordings to date.

Southern California

Starting in July 2000, an array of up to 5 ARPs has been deployed near San Clemente Island off southern California in approximately 200 m water on the Cortez and Tanner Banks (Table 1). At this site, the ARPs are typically configured to sample at 1 kHz, and to be retrieved and serviced every two months. Visual surveys are conducted during these visits to provide a correlation between whale sightings and recorded acoustic data. During the winter months, when whale populations are low, alkaline battery packs are exchanged for lithium packs so that longer (6-month) recording periods are possible. The objective of this study is to obtain long-term (multiple year) recordings of baleen whales, primarily blue (*Balaenoptera musculus*) and fin (*Balaenoptera physalus*) whales, and to develop population and abundance estimates of the calling whales.

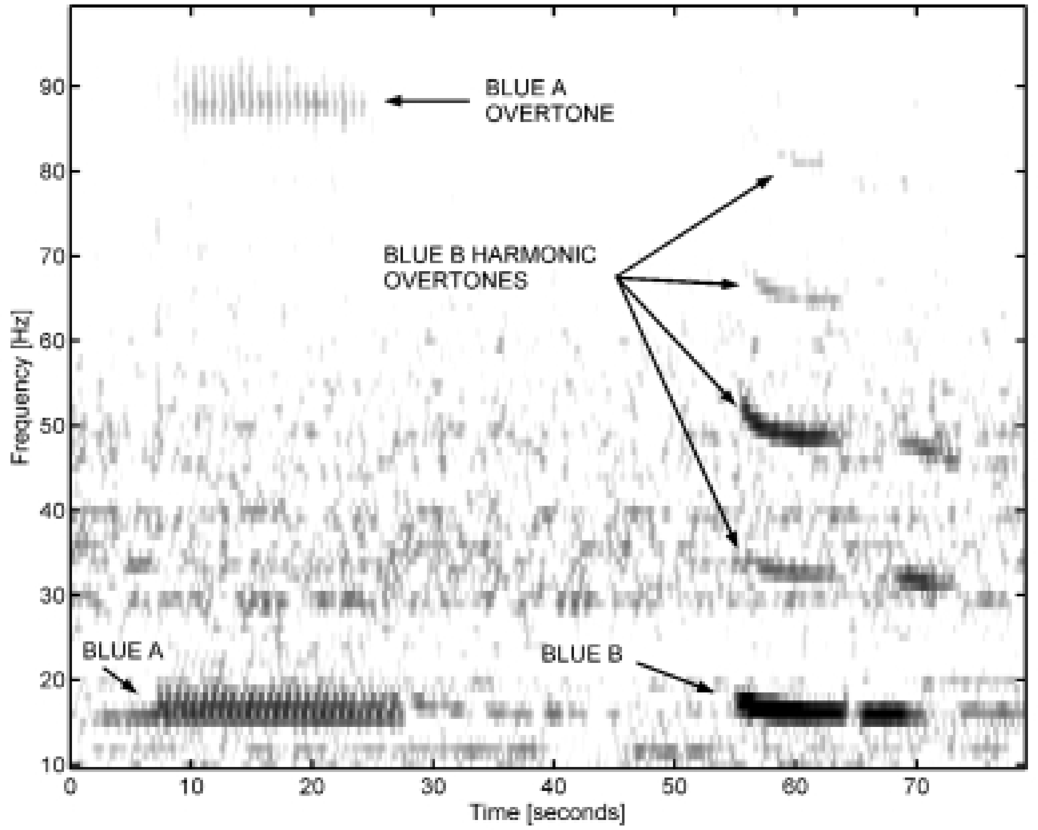
Northeastern Pacific blue whale calls off California's coast are some of the best studied of baleen whales. Their call characteristics have remained consistent over the past 40 years (Thompson, 1965; McDonald et al., 2001), and have 3 main call designations: A, B, and D type calls (McDonald et al., 1995; Thompson et al., 1996; Stafford et al., 1999; McDonald et al., 2001). Blue whale A and B calls recorded near San Clemente Island using an ARP are shown in Figure 4. The A call has energy near 17 Hz and 88 Hz and is pulsed at about once per second, lasting around 20 s. The B call sweeps from around 18 Hz down to 16 Hz in about 2–3 s, and then is tonal for around 15 s. Notice the multiple harmonic overtones of the B call.

Bering Sea

Beginning in October 2000, four ARPs were deployed in the shallow (80 m) Bering Sea near Alaska (Table 1). The objective of this study is to record endangered northern Pacific right whale (*Eubalaena japonica*) vocalizations to provide a means of acoustically surveying the presence of this population which has been seen in the eastern Bering Sea each July since 1996 (Goddard and Rugh, 1998; Moore et al., 2000; LeDuc et al., 2001; Tynan et al., 2001). These instruments were configured to record at 500 Hz for about 8 months using lithium battery packs. In the fall of 2001, two of the ARPs were recovered during a scheduled field operation. Local fishermen located the other two at distant locations from the drop sites. Forensic analysis of the 'wayward' instruments suggests they were dragged off the bottom presumably by fishing operations that take place in this highly productive region.

Both northern Pacific right whale and fin whale calls from the Bering Sea recorded in October 2000 are shown in Figure 5. The right whale calls are upswept calls starting around 100 Hz and ending about 1 s later around 170 Hz. These calls are identical to those reported

Figure 4. ARP data recorded at 1000 Hz in southern California waters illustrating call types from a blue whale. The pulsed signal is an A call, and the mostly tonal signal is a B call. The spectrogram was generated using a Hanning window, 90% overlap and 1000-point fast Fourier transform (FFT).



in the only documented case of northern Pacific right whale concurrent visual and acoustic recordings (McDonald and Moore, 2002). The fin whale calls are down sweeps from near 30 Hz to about 15 Hz, and lasting about 0.5 s. These calls are similar to fin whale calls recorded by ARPs in southern California, and are similar to those well documented in the Northern Hemisphere (Watkins, 1981; Edds, 1988; McDonald et al., 1995; Stafford et al., 1999). Note the greater abundance of fin whale calls compared to the right whale calls.

Antarctica

Beginning in March 2001, seven ARPs were deployed in the Southern Ocean west of the Antarctic Peninsula to determine minimum population estimates, distribution, and seasonality of baleen whales, primarily blue, fin, minke (*Balaenoptera bonaerenis*), and humpback (*Megaptera novaeangliae*) whales (Table 1). These ARPs were configured to record at 500 Hz for more than one year. In February 2002, the ARPs were recovered from both shallow (~300 m) and deep water (~3500 m) locations. Full data disks and used batteries were exchanged for new ones, and the instruments were re-deployed for another one year recording session. A blue whale call recorded with an ARP in the Antarctic is shown in Figure 6. The call starts out tonal near 27 Hz, lasts for about 11 s, sweeps down to 19 Hz in less than 1 s, then is tonal for about 6 s. This call is similar to those reported around Antarctica (Ljungblad et al., 1998; Matsuoka et al., 2000). Note the distinct differences between the blue whale calls recorded in the northeastern Pacific and the Antarctic blue whale call (Figures 4 and 6), suggesting separate stocks of animals (McDonald et al., 2003).

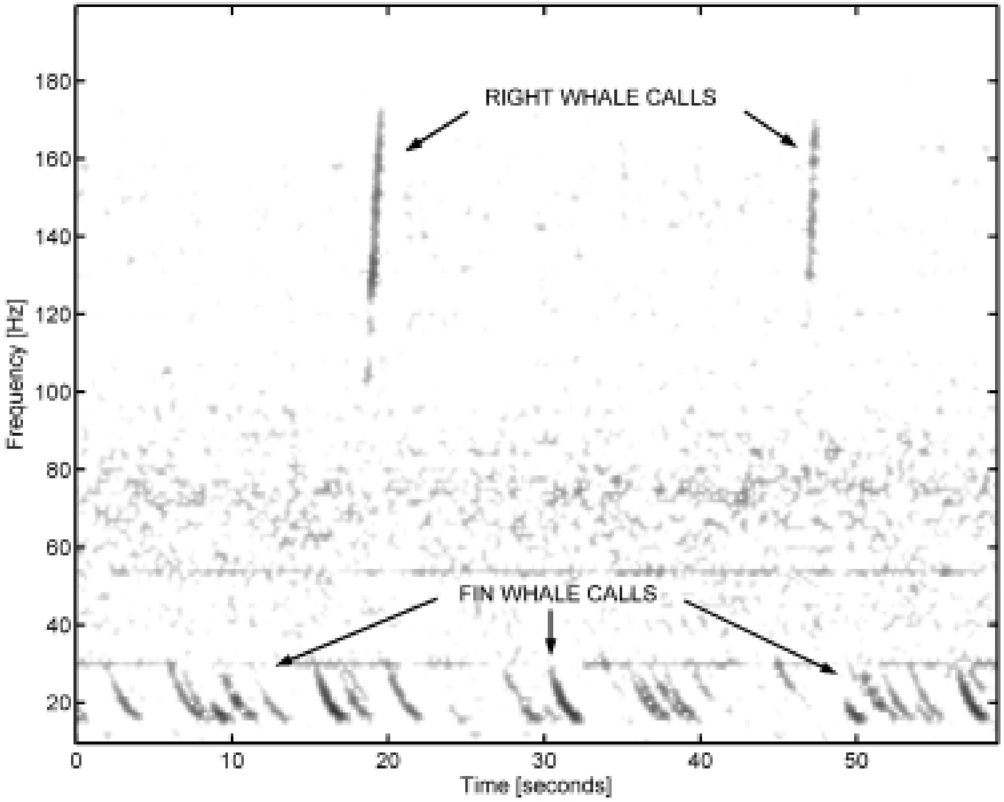
Hawaii

Starting in December of 2000, one ARP was deployed south of Hawaii in ~2500 m deep water and configured to sample at 500 Hz for about 8 months (Table 1). The instrument was recovered with full data disks. This study is part of a seafloor geodetic experiment to record earthquakes, but humpback, fin, and some blue whale vocalizations have been recorded and are currently being analyzed.

Current Sites

Deployments and recordings using ARPs are continuing off the coast of southern California, the Bering Sea, and in the Drake Passage off the West Antarctic Peninsula. New deployments have been conducted in the Gulf

Figure 5. ARP data recorded at 500 Hz in the Bering Sea illustrating two types of whale calls are shown. Fin whale calls are the lower frequency downswept signal, and northern Pacific right whales calls are the upswept mid-frequency signals. The spectrogram was generated using a Hanning window, 90% overlap and 500-point FFT.



of Alaska, in the Beaufort Sea and around the Antarctica continent off Elephant Island and near Mawson.

DISCUSSION

As computer technology continues to advance, further improvements in low-power, long-term, autonomous acoustic data acquisition systems will take place. Figure 7 shows the history of recording capacity for seafloor autonomous recording instruments based on ocean-bottom seismometer (OBS) and ARP technology over the past 25 years. Note that the rate of increase in storage capacity for autonomous instruments is around a factor of 10 every 5 years (factor of 2 per year). This is greater than Moore's law of doubling data storage capacity every 18 months, although ultimately the rate of increase must be limited with this technology. It became possible in the early 1990's to acoustically monitor baleen whales using autonomous instruments, for example, OBSs with 9 GB storage capacity (McDonald et al., 1995). The ARP is at year 2000 and 72 GB capacity and trends predict TB capacity will soon be available.

Continuing this increasing trend is a wider bandwidth acoustic recording package called a HARP (high-frequency acoustic recording package). The HARP is currently being developed to record odontocete vocalizations. Estimations for HARP power consumption at sample rates up to 50 kHz are similar to an ARP sampling at 1 kHz, therefore, about the same amount of battery space will be needed. This will allow for many of the same components to be used such as pressure cases, end caps, flotation, and frame. Sample rates up to 100-200 kHz may be possible with data recorded on low-power, laptop-type disk drives. The HARPs will be configured with 16 small form-factor 60 or 80 GB disk drives for a capacity of around 960 GB or 1.2 TB, respectively. At 50 kHz sampling, the 16-bit data will require about 8.6 GB per day, allowing for over two months of continuous recordings. Alternatively, at 15 kHz sampling, one full year of data can be recorded.

An alternative to continuous recordings would be to implement triggering algorithms in the data logger so that only predetermined call types would be recorded, resulting in much smaller quantities of recorded data. While this approach seems reasonable, many unpredicted calls would go unrecorded. For example, in the Antarctic data set there are many pinniped recordings, but these sounds would not have been recorded by a triggering algorithm set to study whales. Furthermore, investigating the structure and variability of

Figure 6. ARP data recorded at 500 Hz near the West Antarctic Peninsula. This call is from a blue whale and contains two tonals connected by a short duration sweep. The spectrogram was generated using a Hanning window, 90% overlap and 1000-point FFT.

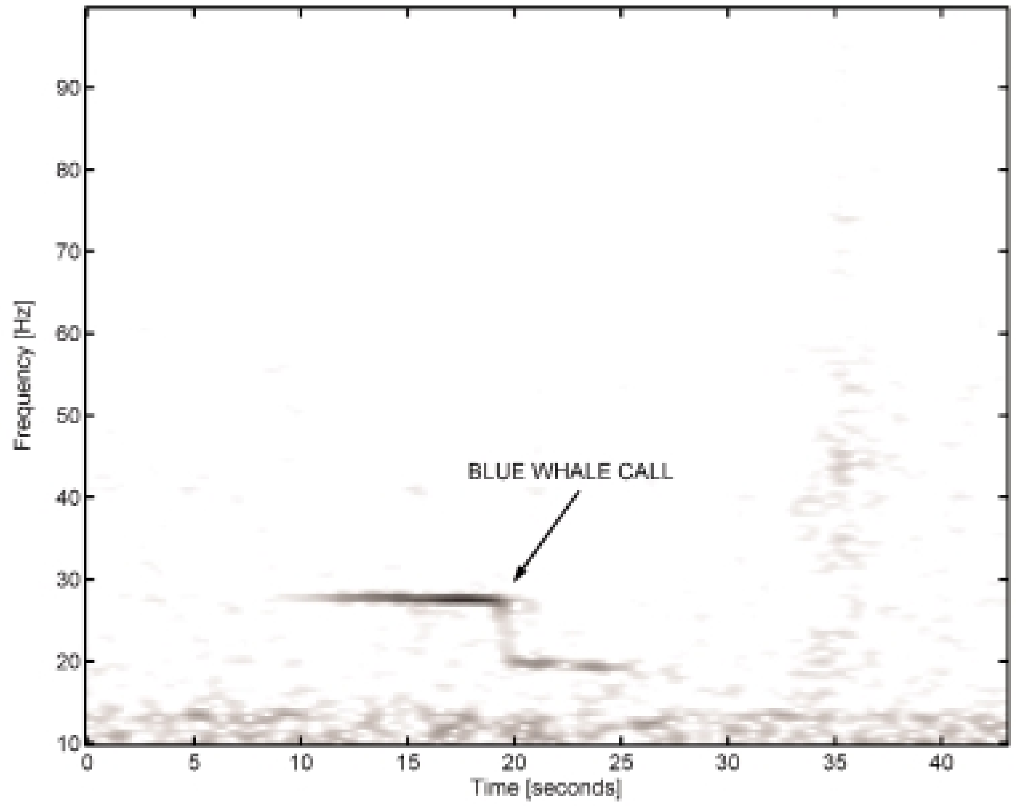
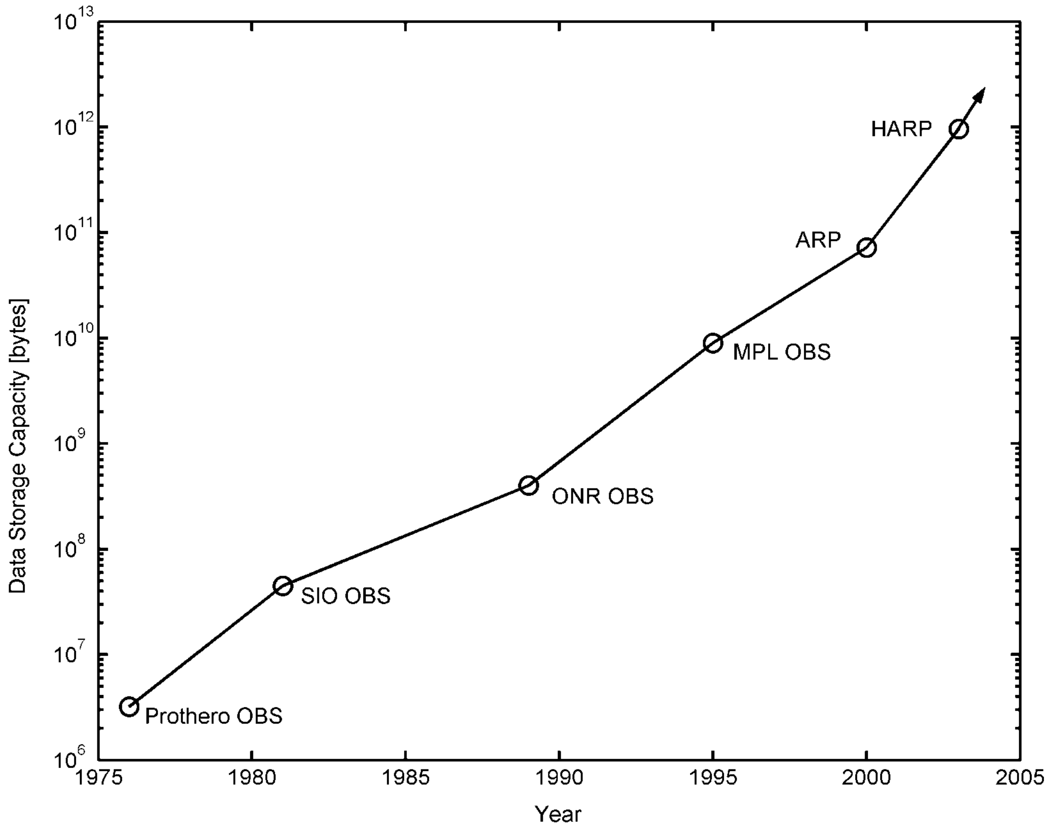


Figure 7. Storage capacity versus time for seafloor autonomous recording instruments. The ARP is at year 2000 and 72 GB capacity. The upward trend in capacity will continue with the development of a HARP (high-frequency acoustic recording package). The other instruments are ocean bottom seismometers (OBS) (Prothero, 1976; (SIO – Scripps Institution of Oceanography) Moore *et al.,* 1981; (ONR – Office of Naval Research) Sauter et al., 1990; (MPL – Marine Physical Laboratory) Sohn *et al.,* 1999). The rate of increase in storage capacity is approximately a factor of 10 every 5 years.



ocean acoustic noise over various time periods would be difficult with event triggered acoustic data.

CONCLUSIONS

Discovering new information about whale population dynamics and whale calls was the intent behind the development of the ARPs. The capabilities of current computer technology have allowed for the development of this system to acoustically monitor calling whales at various sites and conditions over long periods of time. Scientific results include species presence at locations and times previously unknown and newly recorded call pattern types. Current development of a broader-band, higher data capacity system is underway so that recordings can be made of high frequency sounds from odontocetes.

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REFERENCES

Curtis, K. R., Howe, B. M. and Mercer, J. A. 1999. Low-frequency ambient sound in the North Pacific: long time series observations. J. Acoust. Soc. Am. 106- (6): 3189–3200.

Edds. P. L. 1988. Characteristics of finback *Balaenoptera physalus* vocalizations in the St. Lawerance River. Journal of Mammalogy 63- (2): 345–347.

Goddard, P. D. and Rugh, D. J. 1998. A group of right whales seen in the Bering Sea in July 1996. Mar. Mammal Sci. 14- (2): 344–349.

LeDuc, R. G., Perryman, W. L., Gilpatrick, J. W. J., Hyde, J., Stinchcomb, C., Carretta, J. V. and Brownell, R. L. J. 2001. A note on recent surveys for right whales in the southeastern Bering Sea. J. Cetacean Res. Manage. (special issue) 2: 287–289.

Ljungblad, D., Clark, C. W. and Shimada, H. 1998. A comparison of sounds attributed to pygmy blue whales (*Balaenoptera musculus brevicauda*) recorded south of the Madagascar Plateau and those attributed to 'true' blue whales (*Balaenoptera musculus*) recorded off Antarctica. Report of the International Whaling Commission 49: 439–442.

Matsuoka, K., Murase, H., Nishiwaki, S., Fukuchi, T. and Shimada, H. 2000. Development of a retrievable sonobuoy system for whale sounds recording in polar region. In: Proceedings of International Whaling Commission Scientific Committee (unpublished), 7pp.

McDonald, M. A., Webb, S. C. and Hildebrand, J. A. 1995. Blue and fin whales observed on a seafloor array in the Northeast Pacific. J. Acous. Soc. Am. 98- (2), Pt. 1: 712–721.

McDonald, M. A., Calambokidis, J. C., Terinishi, A. and Hildebrand, J. A. 2001. The acoustic calls of blue whales off California with gender data. J. Acoust. Soc. Am. 109: 1728–1735.

McDonald, M. A. and Moore, S. E. 2002. Calls recorded from North Pacific right whales (*Eubalaena japonica*) in the eastern Bering Sea, J. Cetacean Res. Manage. 4- (3): 261–266.

McDonald, M. A., Hildebrand, J. A., and Mesnick, S. 2003. Biogeographic characterization of blue whale song worldwide. In: Proceedings of International Whaling Commission meeting 2003, SC/55/SH 7, Berlin, Germany.

Mellinger, D. K. 2002. Ishmael 1.0 User's Guide, NOAA Technical Memorandum OAR PMEL-120, available from NOAA/PMEL, 7600 Sand Point Way NE, Seattle, WA 98115-6349.

Moore, R. D., Dorman, L. M., Huang, C. Y. and Berliner, D. L. 1981. An ocean bottom microprocessor-based seismometer. Mar. Geophys. Res. 4: 451–477.

Moore, S. E., Waite, J. M., Mazzuca, L. L. and Hobbs, R. C. 2000. Mysticete whale abundance and observations on prey association on the central Bering Sea shelf. J. Cetacean Res. Manage. 2- (3): 227–234.

National Marine Fisheries Service. 1998. Recovery plan for the blue whale (*Balaenoptera musculus)*. Prepared by Reeves, R. R., P. J. Clapham, R. L. Brownell, Jr., and G. K. Silber for the National Marine Fisheries Service, Silver Spring, MD. 44 pp.

Prothero, W. A. 1976. A digital Event-recording ocean bottom seismometer capsule. Mar. Geophys. Res. 3: 119–141.

Richardson, W. J., Greene, C. R., Malme, C. I. and Thomson, D. H., 1995. Marine mammals and noise. San Diego: Academic Press., xvi+576 pp.

Sauter, A. W., Hallinan, J., Currier, R., Barash, T., Wooding, B., Schlutz, A. and Dorman, L. M. 1990. A new ocean bottom seismometer. In: Proceedings of Conference : Marine Instrumentation '90, pp. 99–104., Washington, D.C.: Mar. Technol. Soc.

Sohn, R. A., Hildebrand, J. A. and Webb, S. C. 1999. A microearthquake survey of the high-temperature vent fields on the volcanically active East Pacific Rise (9° 50' N). J. Geophys. Res. 104- (B11): 25,367-25,377.

Stafford, K. M., Niewkrik, S. L. and Fox, C. G. 1999. Low-frequency whale sounds recorded on hydrophones moored in the eastern tropical Pacific. J. Acoust. Soc. Am. 106- (6): 3687–3698.

Tiemann, C. O., Porter, M. B. and Hildebrand, J. A. 2002. Automated model-based localization of marine mammals near California. In: Proceedings Oceans 2002, pp. 1360-1364., Biloxi, Mississippi: MTS/IEEE.

Thompson, P. O., 1965. Marine biological sound west of San Clemente Island: Diurnal distributions and effects of ambient noise level during July 1963. Research report U.S. Navy Electronics Laboratory, San Diego, CA.

Thompson, P. O., Findley, L. T., Vidal, O. and Cummings, W. C. 1996. Underwater sounds of blue whales, *Balaenoptera musculus*, in the Gulf of California, Mexico, Marine Mammal Sci. 12-(2): 288–293.

Tynan, C. T., De Master, D. P. and Peterson, W. P. 2001. Endangered right whales on the southeastern Bering Sea shelf. Science 294: 1,894.

Watkins, W. A., 1981. Activities and underwater sounds of fin whales. Scientific reports of the Whale Research Institute 33: 83–117.