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High-frequency Acoustic Recording Package (HARP) for broad-band, long-term marine mammal monitoring

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Abstract - **Advancements in low-power and high-data-capacity consumer computer technology during the past decade have been adapted to autonomously record sounds from marine mammals over long periods. Acoustic monitoring has advantages over traditional visual surveys including greater detection ranges, continuous long-term monitoring in remote locations under various weather conditions and independent of daylight, and lower cost. However, until recently, the technology required to autonomously record whale sounds over long durations has been limited to low-frequency (< 1000 Hz) baleen whales. The need for a broader-band, higher-data capacity system capable of autonomously recording toothed whales and other marine mammals for long periods has prompted the development of a High-frequency Acoustic Recording Package (HARP) capable of sample rates up to 200 kHz. Currently, HARPs accumulate data at a rate of almost 2 TB per instrument deployment which creates challenges for processing these large data sets. One method we employ to address some of these challenges is a spectral averaging algorithm in which the data are compressed and viewed as long duration spectrograms. These spectrograms provide the ability to view large amounts of data quickly for events of interest, and they provide a link for quickly accessing the short time-scale data for more detailed analysis. HARPs are currently in use worldwide to acoustically monitor marine mammals for behavioral and ecological long-term studies. The HARP design is described and data analysis strategies along with software tools are discussed using examples of broad-band recorded data.**

I. INTRODUCTION

Used as a method for monitoring marine mammals, underwater acoustic recordings have provided ecological, geographical, and behavioral information on a variety of species. For example, recorded calling patterns have given clues to whales' daily calling behavior and seasonal presence (e.g., [1],[2]). Also, acoustic monitoring can aid in studying behavioral responses of calling animals to acoustic events, either anthropogenic or natural. When combined with other data such as visual, environmental and satellite measurements, long-term acoustic monitoring can be an especially powerful observational tool for studying marine mammals.

Since the 1990's several forms of autonomous acoustic monitoring systems with various capabilities have been developed and used in various settings throughout the world's oceans for recording whale sounds (e.g.,[1],[3]-[7]). However, these systems have been limited in sample rate and record only low-frequency baleen whales (<1000 Hz) such as blue (*Balaenoptera musculus*), fin (*B. physalus*), humpback (*Megaptera novaeangliae*), and right (*Eubalaena spp.*) whales. More recently, autonomous acoustic systems capable of higher sample rates have been used in very small packages attached to whales for behavioral studies [8] and in larger packages for seafloor deployment in very shallow water [9], but these newer systems are not capable of providing both long-term (months) and broadband (up to 100 kHz or more) recordings which are required for monitoring toothed whales (odontocetes) (e.g., [10]). As the need grows to conduct long-term studies on odontocetes to learn about their behavior and population dynamics, including understanding their responses to anthropogenic sounds, autonomous recorders with enhanced capabilities are required.

Until recently, long-term high-bandwidth acoustic monitoring was not feasible using autonomous instruments because of data acquisition hardware limitations. However, with the proliferation of new, low-power consumer electronics such as laptop computer hard disk drives, low-power microprocessors, and high-speed digitizers, these limitations can be overcome. In this paper, we describe an instrument called HARP (High-frequency Acoustic Recording Package) which is capable of recording long-term, high band-width acoustic data. We present example data to show some of the challenges and current solutions for processing these high-capacity data sets.

II. METHODS

A. Data Logger Design

To provide long-term acoustic records of odontocete calls from an autonomous instrument, there are three main requirements for the data acquisition electronics: low-power, high-speed digitizing, and high-capacity data storage. As with any battery-powered autonomous instrument, low-power components are essential for long duration deployments. High-speed digitizing is needed to record broad-band odontocete calls and to provide enough bandwidth for call differentiation. High-speed digitizing coupled with long duration recordings requires high-capacity data storage be used. Various forms of digital data storage devices are currently available, but laptop computer disks were chosen because their widespread use in the consumer electronics market allows them to be cost effective and readily available. Furthermore, their design provides a rugged, small form factor (high capacity density), and most importantly, low-power device; all desired characteristics which will likely continue to improve.

We use 16 integrated drive electronics (IDE) laptop disk drives (2.5" form-factor) for our high-capacity data storage. The disks are arranged in a block and are addressed sequentially with all disks connected to a common 50-pin bus (Fig. 1). Only one disk is addressed and powered at a time. To allow for efficient instrument refurbishment, the block of 16 full disks can be easily removed and replaced with a new block of recently formatted disks upon instrument recovery. The removed disk block then can be connected to a computer and the data can be uploaded to a smaller number of large capacity desktop computer disk drives for data backup and analysis. In 2003, 40 GB laptop computer disk drives were readily available and provided a total of 640 GB per deployment. In early 2006, 120 GB disks became cost effective and allowed for a total of 1.92 TB of data space per deployment. It is anticipated that the disk capacity increasing trend will continue for the near future.

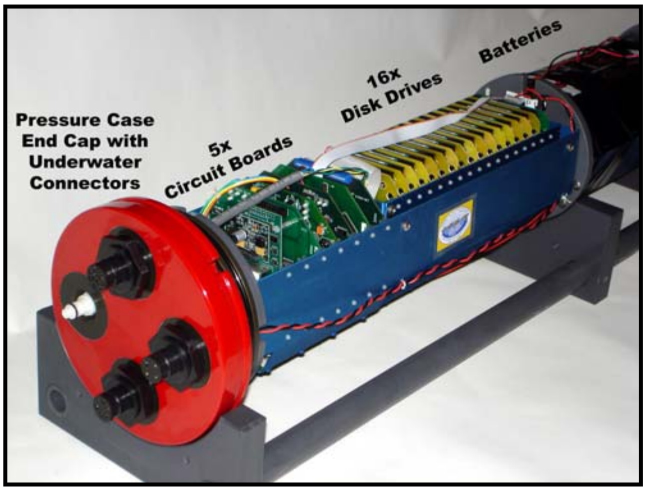

Fig. 1. HARP data logger mounted on aluminum pressure case end cap (7" diameter x 2" thick) with underwater connectors. The data logger consists of a backplane populated with five primary printed circuit boards (clock, A/D, CPU, RAM, Ethernet/IDE controller), a disk block with 16 laptop computer disk drives and 48 D cell alkaline batteries. Another pressure case filled with alkaline batteries can be included for long-term deployments.

In addition to the disk block, the data logger consists of five printed circuit boards (PCBs) connected via 96-pin connectors to a backplane circuit board (Fig. 1). The backplane has two additional connectors for future PCB enhancements. The five PCBs are identified as the central processing unit (CPU), analog-to-digital converter (ADC), static random access memory (SRAM) buffer, Ethernet/IDE communication, and clock cards. The primary component on the CPU card is a 32-bit, 20 MHz microcontroller from Motorola (http://www.motorola.com) which controls all data logging operations. Also included on the CPU card are FLASH memory chips for data buffering and a RS232 transceiver for user communication with the data logger via a standard computer terminal with a serial communications port. For converting the analog sensor signal into digital data, a low-power, low-noise ADC from Analog Devices (http://www.analog.com) was chosen that provides 16-bit resolution and up to 250,000 samples/second sample rate. Eight sample rates ranging from 2000 to 200,000 Hz were chosen to be available for various mission configurations and are software selectable prior to mission initiation. Also included on the ADC card are a power supply for the hydrophone sensor and a 4-pole anti-alias filter for the analog signal that can be easily modified for the various sampling corner frequencies. The SRAM card consists of 32 MB of data buffer space in the form of sixteen 2 MB chips. After digitizing, the data are stored in the SRAM buffer until about 30 MB is occupied, at which point one of the disk drives is turned on and the data are flushed to the disk while the ADC continues to fill up the free buffer space on the back end. The disk writing process requires about one minute to complete and then the disk is turned off. The Ethernet/IDE card provides 10BaseT file transfer protocol (FTP), telnet connectivity, and IDE communication between the data logger and the disk drives. The FTP functionality can be used to upload individual 30 MB files from the data logger disks (i.e., individual SRAM buffer flushed disk writes) without connecting the disk block directly to a computer. Uploading these files through the data logger housing allows the data acquisition system to be evaluated and tested prior to deployment and allows the data quality recorded on the seafloor to be evaluated immediately after recovery without opening the housing. The final card is the clock card which is populated with a temperature compensating phase-lock circuit and a low-power Seascan clock oscillator module which provides low, long-term clock drifts on the order of 1 part in 10^{-8}. Precise clocks are needed for tracking calling whales with multiple instruments deployed in an array configuration.

Data storage capacity dictates monitoring duration and sample rate. The 1.92 TB data storage capacity allows for approximately 55 days of continuous sampling at 200 kHz or about one year continuously at 30 kHz. To extend monitoring durations when using high sample rates, non-continuous sampling can be used; for example, record five continuous minutes on a 10 minute duty cycle. However, there is a tradeoff between minimizing the non-sampling period and maximizing the monitoring duration which must be considered along with the scientific monitoring requirements and species temporal acoustic behavior. For example, a sampling scheme of 12 hrs on and 12 hrs off each day would not provide adequate data coverage to test for a diel calling pattern hypothesis.

The rate at which power is consumed by the data logger is dependent on sample rates and data acquisition sampling schemes (i.e., continuous or non-continuous). Approximately 250 mW is required by the data logger during sampling at the maximum sample rate, but only about 25 mW when in the non-sampling mode. The disks require an additional 2.2 W for one minute while writing data and peak near 5 W upon initial disk spin up.

Batteries are required to operate HARPs autonomously, and the longer the deployment and the higher the sample rate, the larger the number of batteries that are needed to accomplish the mission. To a large extent, batteries drive the design of an autonomous instrument packaging, for instance, pressure cases are often used to house the batteries and additional instrument flotation is required to buoy the weight of the batteries during instrument recovery. In the current HARP seafloor instrument configuration, a total of 192 D size alkaline cells (140g each) are arranged in four sub-packs. Each 14.5 cm diameter sub-pack has 48 D cells arranged in four layers of 12 cells. Twelve Volts per sub-pack are provided by six parallel strings of 8 cells in series, and all sub-packs are connected together in parallel between pressure case housings via underwater cables and bulkhead connectors. One sub-pack is housed with the data logger electronics and provides power for testing the data acquisition system without the need of the additional sub-packs packaged in the battery-only pressure case. For this configuration of twenty-four 12 V strings, an estimated 330 Amp-hours are available per deployment. When recording continuously at the maximum sample rate, the disks become full before the battery pack capacity is reached, but as disk capacity continues to increase, additional alkaline batteries or higher energy capacity batteries (e.g., lithium chemistry) will be required. An alternative approach to housing the batteries with the instrument package would be to jettison the battery pack during instrument recovery resulting in less required buoyancy and smaller instrument packaging.

B. *Hydrophone Design*

The HARP acoustic sensor is a broad-band (10 Hz - 100,000 Hz), low-power (50 mW), high-sensitivity (more than -120 dB re 1V/µPa) hydrophone which includes two types of transducers and signal conditioning preamplifiers, pre-whitening filters and anti-alias filter electronics. To produce a hydrophone that has low self-noise, high gain (over 80 dB), and can pre-whiten the ocean ambient noise across four frequency decades, we developed a hydrophone with two separate stages of signal conditioning, one for the frequency band from 10 Hz to 2000 Hz, and the other from 1000 Hz to 100,000 Hz. After signal conditioning, the signals for the two stages are added together via a differential receiver before being digitized by the ADC and stored on disk.

The two stages use different transducers and provide the ability to record both baleen whale low frequency sounds and high frequency sounds from odontocetes. The high frequency stage uses a spherical omni-directional transducer (ITC-1042, www.itc-transducers.com) which is constructed from lead zirconate titanate ceramic and has an approximately flat (+/- 2 dB) sensitivity response of about -200 dB re 1Vrms / µPa from 1 Hz to 100 kHz. The low frequency stage uses six cylindrical transducers (Benthos AQ-1, www.benthos.com) connected in series to provide a total sensitivity of about -187 dB re 1Vrms / µPa with a flat response (+/- 1.5 dB) from 1 Hz to 10,000 Hz. The signals from the transducers are fed into preamplifiers with approximately 40 dB of gain for the low frequency stage, and about 80 dB for the high frequency stage. The signals are pre-whitened with a frequency response similar to the reciprocal of the ocean ambient noise as a function of frequency (i.e., ocean ambient noise decreases as frequency increases; [11]). The pre-whitening filter flattens the response of the hydrophone system in the presence of ocean ambient noise, adding more gain at higher frequencies where ambient noise levels are lower and sound attenuation is higher. The pre-whitening is accomplished through the two preamplifiers and through the low-end rolloffs of the high-pass filters of the two stages (i.e., below 30 Hz on the low frequency stage and below 10 kHz on the high frequency stage). After pre-amplifying and pre-whitening, a 4-pole low-pass filter is used to reduce high-frequency aliasing effects (above 2 kHz for the low frequency stage and above 100 kHz for the high frequency stage). Line drivers send the signals separately through a 10m cable to a differential receiver in the data logger which combines the signals, and another 4-pole low-pass filter with a -3 dB point at 100 kHz is included in the data logger to further reduce high frequency aliasing effects. Fig. 2 shows the hydrophone system sensitivity as a function of frequency.

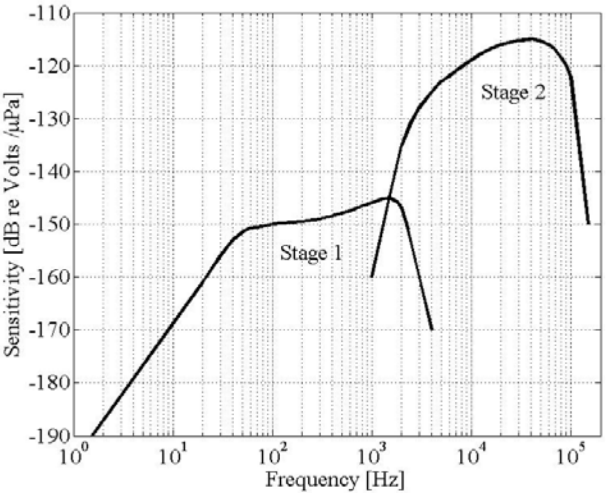

Fig. 2. Hydrophone sensitivity plot showing two stages of preamplification, pre-whitening, and anti-aliasing filters. The shape of the hydrophone sensitivity was designed to follow the reciprocal of ocean ambient noise so that the sensor's response would allow for large amplitude signals across the wide band of frequencies above ambient noise.

The transducer and signal conditioning electronics are packaged in a soft, oil-filled polyurethane tube to provide good acoustic coupling with the seawater. The signal conditioning surface mount electronics are populated onto a 2 cm x 8 cm, two-sided printed circuit board which is mounted on a bulkhead connector to allow easy electronics changing based on experimental requirements (i.e., different sample rates require different anti-alias and pre-whitening filters).

C. *Seafloor Package Design*

The size of a HARP seafloor package is dictated by the requirement to buoy and bring back to the sea surface the data logger and acoustic release electronics, pressure cases, frame, and about 27 kg of batteries. The batteries are the major weight component of the system, but also control the deployment duration. Currently, the HARP seafloor package has about 60 kg of buoyancy in the form of six 30.5 cm diameter glass spheres rated to 6600m (Fig. 3).

The seafloor HARP has an acoustic release system which utilizes an EdgeTech (www.edgetech.com) electronic board and ITC transducer to receive acoustic commands from a support ship and in turn power a motor activated release of the ballast weights. The ballast weights are standard athletic weight lifting plates and are readily available worldwide. In addition to being lower cost than fabricating comparable ballast weights, these plates come with a center mounting hole, are smooth and appropriate size for easy handling and stacking, and are painted which reduces rust accumulation during transport and storage. Two acoustic release systems can be used on one seafloor package to provide a redundant system and increase the likelihood of instrument recovery in the event of failure of one of the release systems.

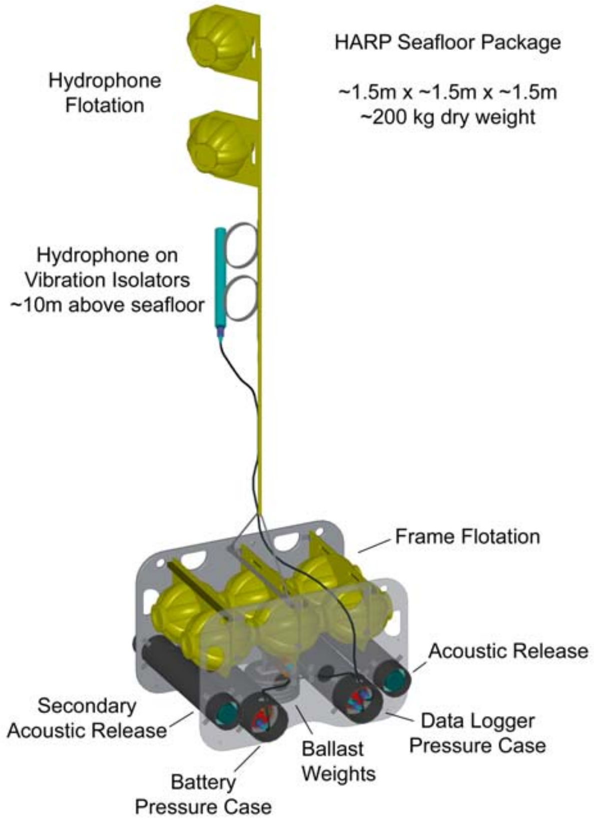

Fig. 3. HARP Seafloor package including data logger and acoustic release electronics pressure cases, ballast weights, glass flotation sphere in yellow hard hats, and hydrophone tethered ~ 10m above seafloor.

High-density polyethylene (HDPE) plastic panels and tubes are used to provide the framework for the seafloor package design. HDPE is low cost, easily machined, durable, and buoyant in sea water. The panels include holes for direct mounting to a ship's deck, for lifting points, and for lines when controlling the package during deployments and recoveries. The panels also act as runners allowing a fully loaded frame to be easily slid on deck into launch position by two people. The HDPE cross-frame tubes house the aluminum pressure cases and provide structural strength for the frame. All frame-fastening hardware is unalloyed titanium to minimize corrosion problems.

The hydrophone sensor is tethered to the seafloor instrument via polypropylene line and buoyed 10 m off the seafloor by floats. The floats are either glass spheres as used to buoy the frame or syntactic foam-filled plastic tubes which are more durable than glass during deployment and recovery operations. The hydrophone is buoyed off of the seafloor to minimize noise from spinning disk drives in the data logger or flow noise from the seafloor package, and to provide reception of acoustically refracted sound waves arriving at low incident angle.

D. Data Processing

Working with long-term, high-frequency (200 kHz) acoustic data collected by HARPs can be challenging because of the large size (2- 12 TB/yr per instrument) of these data sets. Just the process of uploading from the raw disks and backing up the large amounts of data can be difficult and time intensive.

Data are uploaded from the 16 raw laptop disks in the disk block to a smaller number of larger form-factor (3.5"), higher capacity disks to make data handling more manageable. The larger disks are also more cost effective than the laptop disks, do not need to be low-power, and typically operate at faster rates. During the uploading process, the data are copied from the HARP specialized file system to a standard file system so that the data can be read by a desktop computer. Each raw HARP disk is copied to a single file (e.g., 120 GB) to provide a complete backup of the original disk. The size of these backup files requires the use of a 64-bit computer so that locations within the file can be addressed to generate smaller and more manageable working files. We use a computer running a Linux operating system and the *dd* command to upload the raw data into the backup files. The backup files are then parsed into smaller (~1 GB) processing files using MATLAB (www.mathworks.com). We found this size to be a good optimization of the tradeoff between having the fewest number of files per instrument-deployment to manage and file sizes small enough to easily process. Also, standard computers and readily available software are currently limited to 32-bit addressing, which prohibits easily working with files larger than about 4 GB.

The 1 GB processing files are generated in a format we call XWAV which is similar to a WAV formatted file but which include additional information in an expanded header. For example, the XWAV header also includes data timing information (i.e., start and stop times), latitude, longitude and depth of instrument deployment, and other experiment specific information. The raw data are evaluated for timing accuracies before including in the XWAV file header. XWAV files have a single header followed by a stream of data as in WAV files to allow for more efficient data processing than a file format with timing headers interleaved throughout the data. XWAV files can be viewed and played with standard audio software that can read WAV files. The XWAV header also can be modified to adjust the gain and speed at which the file is played in standard audio software, but still retain the original amplitude and sample rate for processing with XWAV-capable software.

Each instrument deployment results in about 2000 XWAV time series files, and viewing and analyzing each one of these files in a non-automated way is not practical, so we use a means of file compression for data overview based on long-term spectral averages (LTSA). Spectral-averaging is a method of searching for acoustic events such as whale calls in long-term data sets (e.g., [12] – [14]). Instead of inspecting short duration spectrograms for individual calls, successive spectra are calculated and averaged together. These averaged-spectra are arranged sequentially to provide a time series of the spectra. The averaging time determines the resolution of the resulting plot and the data compression factor. Essentially, spectral-averaging is a spectrogram over long time periods and provides a coarse map or table of contents to groups of events in the finer time scale XWAV data. Depending on number of samples used for the spectra and the averaging time used, data compression factors of 4000 or more are possible while still providing enough resolution to observe short-term events above the ambient noise.

III. RESULTS

As an example of our processing technique, an LTSA was generated from HARP data sampled at 200 kHz offshore of southern California in the fall of 2006 and is shown in Fig. 4. The two hour LTSA was calculated using 1000 point fast fourier transforms (FFTs), Hanning windows, no overlap, and averaged over 5 seconds. Figure 4 shows quiet periods for approximately the first and last one-third hours, with sounds of various intensities and frequencies in-between. In this data set, marine mammal sounds with similar characteristics lasting one to two hours occur only two to four times per day, so a large portion (70% – 90%) of these data do not contain calls, but with the LTSA technique, the quiet times can be easily passed over during analysis.

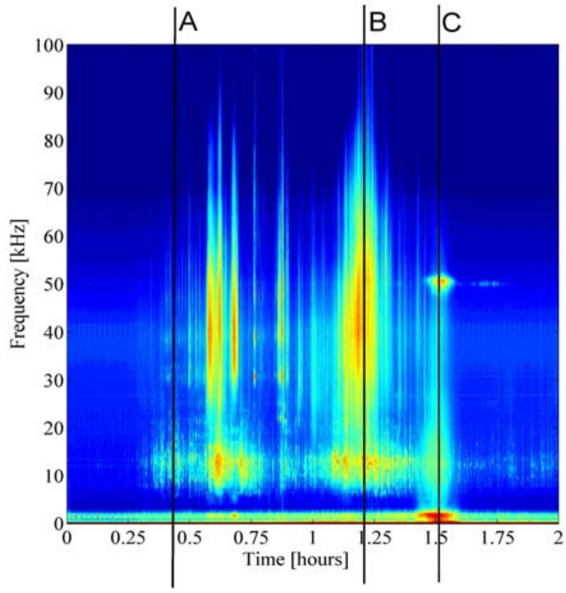

Fig. 4. Two hour long-term spectral average (LTSA) from a site south of Santa Catalina Island, offshore of southern California and approximately 330m deep. The LTSA was generated using 1000 point FFTs, Hanning windows, no overlap and averaged every 5 seconds on HARP data recorded at 200 kHz. Sections A, B and C are shown as uncompressed spectrograms in Fig. 5

Three different sections of the LTSA in Fig. 4 denoted by thin vertical black lines at approximately 0.4, 1.2, and 1.5 hours and are labeled A, B, and C, respectively. The corresponding short time-scale spectrograms are calculated and shown in Fig. 5. These spectrograms use 1000 point FFTs, Hanning windows, and no overlap. Fig. 5a shows mostly dolphin whistles from around 5 – 30 kHz, whereas, Fig. 5b is full of broadband clicks from about 20 kHz to presumably beyond our recording Nyquist frequency, and many intense whistles at lower frequencies. Matching these characteristics back to the LTSA plot shows most of the energy from the whistles is clustered between 8 – 18 kHz and clicks are broad-band events primarily between 20 and 70 kHz. The spectrogram of Fig. 5c is not from dolphins but from a passing boat using a 50 kHz echo sounder which is easily observed in both Fig. 4 and Fig. 5c in addition to the wideband noise at low frequency (< 2 kHz) presumably from the boat propulsion system.

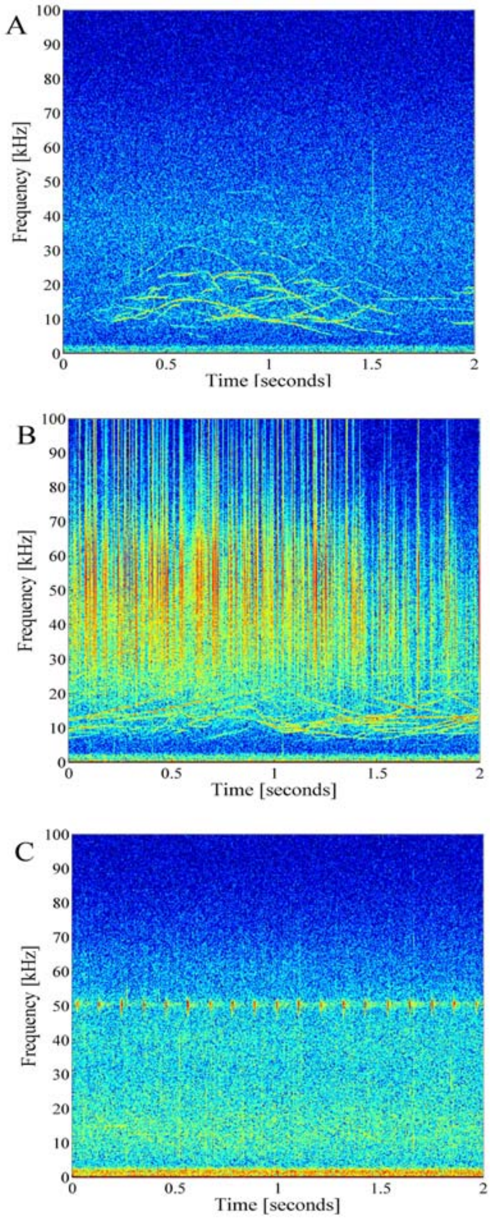

Fig. 5. Short time-scale spectrograms corresponding to sections A, B and C from Fig. 4. Spectrograms were calculated using 1000 point FFTs, Hanning windows, and no overlap. Note A and B are recordings of dolphins where as C is from a passing boat with a 50 kHz echosounder.

IV. DISCUSSION

The motivation for HARP development is based on providing enhanced capabilities to record mid-frequency whistles and high frequency clicks from toothed whales over long periods. While the preceding examples show we have accomplished these goals along with the ability to record low frequency baleen whales and anthropogenic noise, we are still striving to improve the HARP's capabilities by increasing its sample rate, data storage capacity and deployment duration.

Currently, HARP deployments are limited in duration by the amount of data storage available and can record for almost two months at maximum sample rate. However, as larger capacity disks become available, longer deployments will be possible with additional batteries. These additional batteries may require HARPs to be deployed as part of large oceanographic moorings where the additional weight can be easily compensated with additional buoyancy. On the other hand, lower power electronics and faster data transfer rates from the memory buffer to data storage disks (i.e., disks are powered for shorter periods) also could provide for longer deployments with the same or fewer batteries. Data compression schemes may provide a means in which to decrease power consumption rates and therefore increase deployment duration, so these approaches also should be investigated. Perhaps in the near future with the advancement of digital cameras and other similar memory devices, low-power, solid-state memory costs will decrease and their storage capacities will increase enough to make it feasible to use these devices to replace the energy-intensive, motorized disk drives currently used in HARPs.

V. CONCLUSION

Long-term, broad-band, ocean acoustic recordings from HARPs can provide detailed information on a variety of sources including natural sounds from baleen and toothed whales, other marine mammals like pinnipeds and sirenians, fish, wind, rain, earthquakes, and from anthropogenic sources such as ships, sonars, and seismic exploration. Not until recently has an autonomous acoustic system been capable of recording mid- to high-frequency sound over long periods and if the trend in consumer computer electronics continues as it has for the past 30 years, we should expect longer-term, higher sample rate, larger capacity, lower cost, and smaller instrument packages to evolve.

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