Acoustic Recording Systems For Baleen Whales And Killer Whales On The West Coast Of Canada

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ABSTRACT

The threat to the survival of several whale species and the introduction of the Species at Risk Act (SARA) has highlighted the need for better knowledge about the biology and ecology of marine mammals in Canadian waters. The North Pacific right whale (*Eubalaena japonica)*, once plentiful across much of the North Pacific Ocean, is now rarely seen in coastal British Columbian waters, and the number of killer whales (*Orcinus orca)* in southern British Columbia has been steadily decreasing in recent years. The recovery plan for these species is based on the gathering of baseline data on occurrence, distribution, abundance and habitat, and one significant component of this data collection is based on the deployment of multiple passive acoustical recording systems off the coast of British Columbia. In addition to the development and use of a simple but effective two-hydrophone array, two different autonomous passive acoustical instruments have been developed, one deployable at shore sites and the other for offshore locations. To limit data storage and power requirements, both of these systems have been equipped with killer whale recognition hardware to record only when the probability of killer whales in the area is relatively high. In addition the offshore units have been designed as hybrid recorders, sampling at 1000 Hz for the larger baleen whales and 20 kHz when killer whales are present. Both of these instruments have been designed for deployment periods as long as 12 months and are presently deployed in locations along the BC coast. The analysis of the large data sets from these instruments is a challenge and we are currently investigating the use of neural network algorithms to perform not only species recognition but also, with regards to the killer whale population, clan or group identification. The goal is to adapt these algorithms directly into the self-contained instruments.

RÉSUMÉ

La menace à la survie de plusieurs espèces de baleines et la présentation de la Loi sur les espèces en péril (LEP) a fait ressortir le besoin d'approfondir nos connaissances au sujet de la biologie et de l'écologie des mammifères marins dans les eaux canadiennes. La baleine franche du Pacifique nord (*Eubalaena japonica),* pourtant abondante autrefois dans une grande partie de l'océan Pacifique Nord, est maintenant rare dans les eaux côtières de Colombie-Britannique, et le nombre d'épaulards (*Orcinus orca)* dans le sud de la Colombie-Britannique a diminué de façon régulière ces dernières années. Le plan de rétablissement de ces espèces est fondé sur la collecte de données de référence concernant la présence, la distribution, l'abondance et l'habitat, et un élément significatif de cette collecte de données se fonde sur le déploiement de multiples systèmes d'enregistrement acoustique passif au large de la côte de la Colombie-Britannique. En plus du développement et de l'utilisation d'un réseau de deux hydrophones, qui est simple mais efficace, deux appareils acoustiques passifs autonomes ont été développés; un appareil pouvant être déployé sur le rivage et l'autre pouvant être déployé au large. Les deux systèmes sont munis de matériel de reconnaissance qui enregistre seulement s'il existe une forte probabilité qu'il y a des épaulards dans la région afin de limiter les exigences en matière de stockage de données et d'alimentation en énergie. En outre, les diapositifs utilisés au large ont été conçus en tant qu'enregistreurs hybrides; le taux d'échantillonnage est de 1000 Hz pour les grandes baleines à fanons et de 20 kHz pour les épaulards. Les deux appareils ont été conçus en vue de les déployer pour un période maximale de 12 mois et ils sont actuellement déployés le long de la côte de la C.-B.. L'analyse des grands ensembles de données provenant de ces appareils est un défi et nous étudions actuellement la possibilité d'utiliser des algorithmes de réseau neurologique pour exécuter non seulement l'identification d'espèce mais, également, l'identification du clan ou du groupe en ce qui concerne la population des épaulards. L'objectif est d'incorporer ces algorithmes directement aux appareils autonomes.

1 INTRODUCTION

A large number of marine mammal species are living in or migrating through the offshore waters of the west coast of Canada, but the understanding of their life cycle and migratory patterns is currently very limited. In addition to the killer whale and the North Pacific right whale, which will be specifically dealt with in this paper, the marine mammal species on the west coast that we are interested in monitoring include fin whales *(Balaenoptera physalus),* blue whales *(Balaenoptera musculus),* humpback whales *(Megaptera novaeangliae),* gray whales *(Eschrichtius robustus),* and sperm whales *(Physeter macrocephalus).* All of these species use acoustic energy for communication and some for echolocation. The frequency band used by the different animals of interest are these: fin whale 14-750 Hz, blue whale 10-390 Hz, humpback whale 30-8000 Hz, gray whale 20-2000 Hz, sperm whale 100-30000 Hz, killer whale 1200-25000 Hz, and North Pacific right whale 20-900 Hz (National Research Council, 2000).

1.1 Killer whale (*Orcinus orca*)

Researchers classify northeastern Pacific killer whales into three distinct populations, or 'ecotypes': "residents" feed exclusively on fish and squid and are very vocal, "transients" prey exclusively on marine mammals and seabirds and are very quiet (Barrett-Lennard et al., 1996; Ford et al., 2000)), and "offshores", which are very poorly known.

The resident killer whales in the northeastern Pacific are the most frequently encountered whales in this region and have been studied for more than 30 years. Large groups of 10-50 animals can often be seen in coastal waters in the summer months, and these groups have consistent and stable memberships. The population assessment of resident killer whales based on photo-identification of individuals using natural markings has identified the presence of complex matrilineal societies(Biggs et al., 1987; Ford et al., 2000). In the late 1970s, Ford began studies of the group specific vocalizations, or dialects, of the resident communities (Ford, 1989,1991). He found that pods have stable repertoires of stereotyped calls and that these repertoires differ among resident pods and matrilines. It has been suggested that these dialects may play a role in defining the group identity and outbreeding. The resident killer whales predominantly vocalize in the 1-10 kHz range. Figure 1 shows examples of spectrograms of vocalizations from two clans, one from the northern community of resident whales and one from the southern community, clearly showing the different dialects of the two groups.

Even though killer whales are protected, the Committee on the Status of Endangered Wildlife of Canada (COSEWIC) has declared the northern community of resident killer whales as threatened and the southern community as endangered. Since 1995 the number of animals in the southern community as declined from about 100 to approximately 80 (Figure 2).

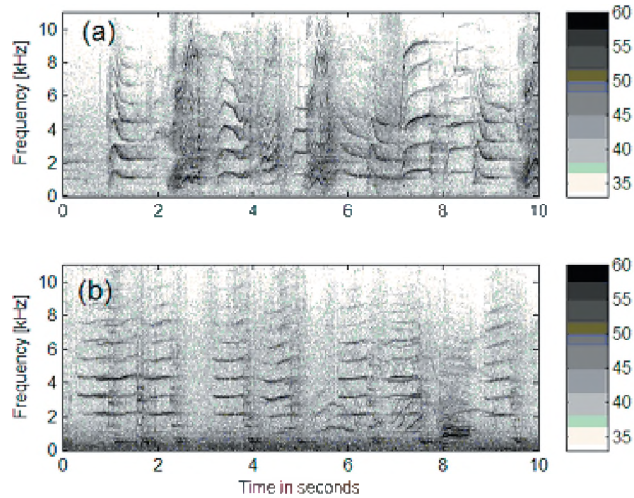

Figure 1. (a) Spectrograms from a northern resident community pod, and (b) a southern resident community pod show the distinct differences between the vocalizations of members of the two killer whale communities. The greyscale represents sound pressure levels in decibels relative to an arbitrary reference.

The reasons for the decline are not known, but factors including vessel disturbance, underwater noise, declining fish stocks, and man-made contaminants have been suggested (Ross et al., 2000). Before any recovery strategy can be successful, we need to learn more about the biology and ecology of these animals. For example, one critical knowledge gap is to understand what they do in the winter months. As can be seen in Figure 3, the majority of the sightings take place in the summer and fall months from May to November. The whales leave the summer core areas in the winter months and their distribution during this period is unknown. Food might be relatively scarce during this period, especially for the salmon-feeding resident communities, and studies have shown that most mortalities take place during this period.

It is therefore crucial for any recovery strategy to study the winter behaviour and habitat of the animals. Vessel- and shore-based visual surveys are very difficult in the winter months. Frequent foul weather periods make it hard to see the animals at the ocean surface, and the number of hours with daylight is limited. Long-term satellite tracking using radio transmitters attached to the whales is also not an option in this region given the animals' endangered or threatened status and the potential risk of harmful effects from surgical tag attachment. Because of the relatively high vocalization rate of the resident killer whales and because of their distinct dialects, these mammals are well suited for monitoring by passive acoustic devices.

1.2 North Pacific right whale (*Eubalaena japonica)*

The North Pacific right whale is a large robust baleen whale that once was plentiful across much of the North Pacific

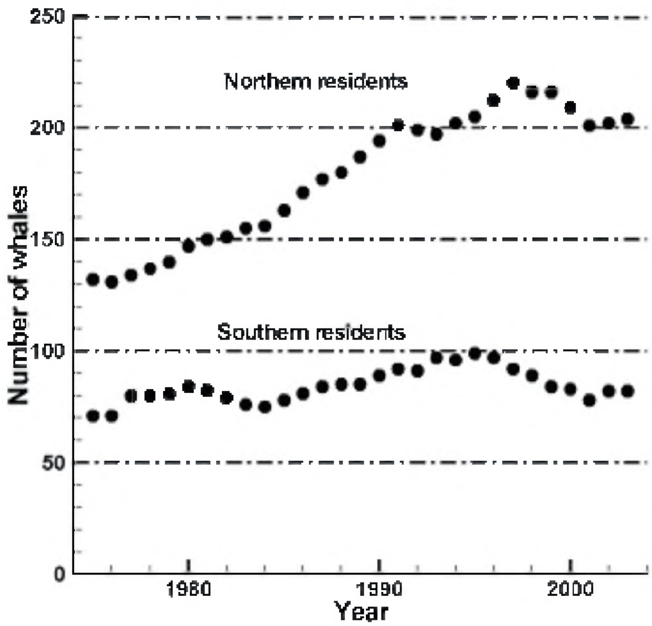

Figure 2. The sizes of the resident killer whale communities from 1974 to 2003 (Ford et al., 2000; Ford, unpublished data)

Ocean but now is rarely seen in coastal British Columbia waters (Rosenbaum et al., 2000). These whales were decimated by whaling during the 1800s and, despite having received international protection since 1935; their numbers have not appeared to recover. Basic aspects of the biology and ecology of the species remain unknown. It is unclear how many individual animals exist and the location of the calving grounds is still a mystery (Brownell et al., 2001). The scarcity of recent sightings suggests that the population may number less than 100, at least in the eastern North Pacific. Causes for the continued low or declining population are not known. However, climate-driven regime shifts are manifested faster at lower trophic levels in the marine echosystems (Benson and Trites, 2002), and an increase in surface water temperature could result in declining zooplankton populations (Roemmich and McGowan, 1995). Right whales feed exclusively on zooplankton, and preferably on large calanoid copepods. They have a narrow range of acceptable

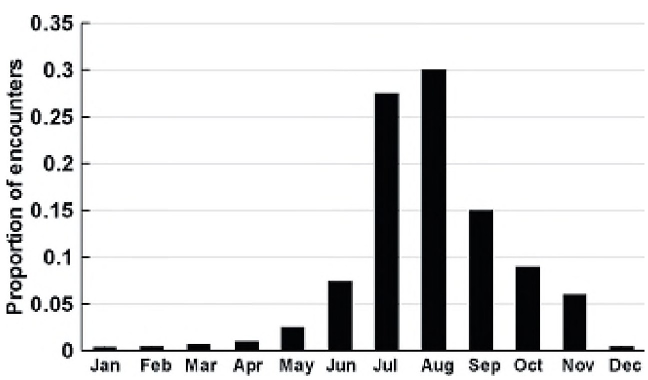

Figure 3. Proportion of northern resident killer whale encounters by month (Ford, unpublished data)

prey species and require prey concentrations of exceptionally high densities, which again are dependent on factors such as nutrient levels, currents and temperature. Kenney (2001) suggested this might make the right whale, which is a low trophic grazer, more sensitive than other cetaceans to impacts from global climate change.

The right whales produce the "up" call, which is a frequency-modulated upsweep in the 50-200 Hz range (McDonald & Moore, 2002). This call is one of the most common calls and is therefore a useful indicator of the presence of right whales for passive acoustic tracking devices (see other papers in this issue).

1.3 Recovery Strategy

Fisheries and Oceans Canada (DFO) has outlined a new a recovery strategy aimed at restoring the North Pacific right whale to Canadian waters and maintaining the long-term viability of the population. To reach this goal, the recovery objectives include; 1) to gather baseline data on occurrence, distribution, abundance and habitat to support recovery efforts and 2) to conduct long-term monitoring of the status of these animals and evaluate the effectiveness of mitigation strategies.

We have developed a three-pronged approach to the use of passive acoustic systems to aid in reaching these goals. *In situ* use of towed arrays can be very useful as a supportive tool in the gathering of baseline data, and self-contained recording instruments, which also can be used to collect baseline data in the earlier stages of the recovery, are well suited for long-term monitoring of the mammal population.

2 BASELINE DATA GATHERING

2.1 Towed arrays

The information from towed hydrophone arrays can add valuable information to visual marine mammal surveys from different vessels. With the use of more than one hydrophone it is possible to obtain directional information relative to the ship heading. Two spaced hydrophones embedded in a single cable and being towed behind a ship will have left-right ambiguity, i.e., it is impossible to know whether the vocalizing animal(s) is on the left or the right side of the vessel. This ambiguity can be resolved by adding a third hydrophone.

An array that can be towed at or near the cruising speed of the vessel allows for large area coverage compared to single hydrophones lowered from stationary platforms. A well-built system can also be operated 24 hours a day and during a range of sea states.

The design criteria we used for our towed hydrophone system are these: 1) the system has to be light weight to accommodate mounting on a variety of different small and large vessels; 2) it has to be easy to use so that the system can be loaded onto a vessel of opportunity with no specially trained operator; 3) it has to be relatively inexpensive to acquire and maintain; and 4) its design must accommodate future implementation of artificial intelligence algorithms for species recognition and operator alarms.

When using ship-based systems, there is in effect no electrical power limitation and no limit to onboard real-time signal processing, something that in many respects simplifies the design when compared to the self-contained battery powered instrumentation discussed below.

Our operational system, as shown in Figure 4 and Figure 5(a), consists of 200 m of armoured cable with a drogue at the far end. The cable is wound on a small electrically operated winch giving a towing length of approximately 170m. The two hydrophones (Biomon model BM212) have a separation of 10 m and an acoustic bandwidth of 1 - 41 kHz with a maximum received response of –151 dB re 1V/μPa. The built-in 1 kHz high-pass cut-off frequency was included to limit the possibility that low-frequency ship noise and flow noise might saturate the hydrophone preamplifier. The signals from the hydrophones are passed through two SRS SR-650 filter units, which act as signal amplifiers (with up to 90 dB gain) and as band-pass filters. The SR-650 units are controllable via RS232 serial protocol from a laptop computer. Typically we have been filtering the signals between 3 and 10 kHz to reduce ship noise while preserving killer whale vocalizations. The amplified and filtered signals are passed to the 'line in' connectors on the laptop and recorded to disc and/or used to estimate source direction and vocalization identification.

Raw data are written to hard drive in VOC format using the built-in sound acquisition system at a rate of 22050 Hz at 16 bits per channel. The VOC format, which is compatible with numerous commercially available playback programs, incorporates different block types allowing additional information such as time stamping, GPS position data and user comments to be recorded. System specifications are listed in Table I.

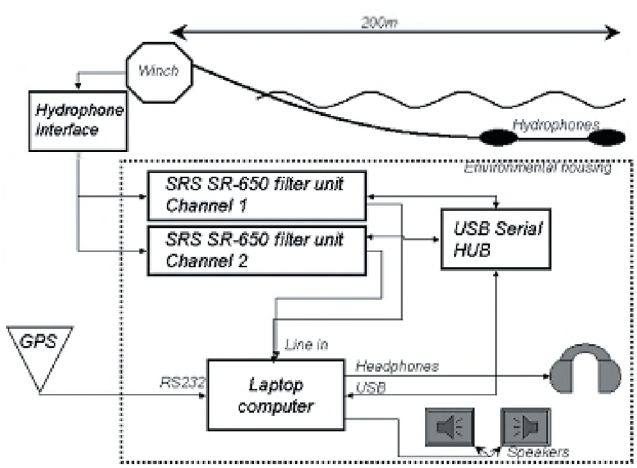

Figure 4: Schematic diagram of towed hydrophone array system.

The software generates a continuous scrolling spectrogram display, and a cross correlation algorithm using a user-defined frequency range generates a user-friendly graphical display showing, in real time, the direction of the sound sources relative to the towing vessel, thus aiding in locating them. Future developments of this system include the incorporation of real time species and group specific vocalization recognition algorithms. The plan is to incorporate these into alarm routines that can inform ship operators and scientist when mammal vocalizations have been detected by the system.

The disadvantages of these types of systems include the cost of ship time and the acoustical noise from the towing vessel and the limited time that any given area can be surveyed. Ship noise entering the hydrophone arrays generally limits their use to higher frequencies and generally limits the monitoring capabilities to the smaller toothed whales. However, towed arrays have been used in sperm whale surveys for many years (e.g., Barlow & Taylor, 1998).

3 LONGER TERM MONITORING

3.1 Shore based monitoring system

For longer term passive acoustic monitoring of killer whales in coastal waters - for example, to determine their location during the winter months - we designed and built a system that can be placed on shore in remote areas with a hydrophone deployed in nearby waters. Such a system must be rugged to withstand winter weather and possible animal attacks as well as having the capability of recording for extended periods up to a year.

The main advantages of our present system are: 1) the relative ease of deployment by two people in a small boat; 2) the ease at which data can be recovered and the instrumentation serviced; 3) the economics of the electrical power supply. (it is easy to add a number of car batteries to a site onshore).

In addition we have implemented solar panels for charging batteries and have been experimenting with the use of wind power for winter deployments in northern waters where the hours of daylight are severely restricted. The system we have designed and constructed, called "Orcabox", is shown in Figure 5(b) and the schematic diagram of the main components is shown in Figure 6.

The underwater part of the system consists of a broadband hydrophone (50-20,000 Hz) deployed at the end of an armoured cable (<200 m). For these types of systems the cable going through the tidal zone is the most vulnerable for longer-term deployments. Several approaches have been attempted to address this problem using different types of conduits, with varying degree of success. The chosen approach will be quite site dependent. A cable with a thick polyurethane coating supplied by "Specialty wiring and Cable" in Calgary, AB has worked very well. However, we have also had good experiences with using old CTD cables for this purpose. The outer steel jacket of a good CTD cable is quite resistant to the chafing in the tidal zone.

The dry end of the armoured cable is connected to a 0.53 m 0.44 m by 0.22 m waterproof case mounted with lead acid batteries in a lockable solid aluminium housing on dry land, away from the wave zone. Solar panels can be positioned at appropriate sites in the vicinity of the aluminium housing (Figure 5(b)). Inside the waterproof case, the hydrophone signal is passed through a preamplifier and an 80 dB automatic gain control (AGC) circuit before going into an analog acoustic pattern recognition circuit (Figure 6). This circuit is designed to recognize killer whale calls and consists of 3 parallel filters; the first two being peaking filters with a Q of about 10 centered on 4 kHz and 14 kHz, and the final one is a 50-450 Hz band-pass filter. The third filter is used to differentiate boat noise from killer whale calls, as there is little energy in that range in whale calls.

The output sine waves from the filters are squared and counted by a microcontroller. The algorithm then looks for a certain number of positive going transitions in the output of these squaring circuits for a given period of time.

When the user-defined conditions are met, this circuit powers up the PC104 computer and the hard drive; then records for a specified period (typically 3-10 minutes) at 20 kHz using 8 bit words. The hard drive in this system is easily replaceable for easy transfer of data.

As before we are using the VOC format to allow for time stamping of the data. (The specifications for this system are also listed in Table I.)

Figure 7 shows the results from a nearly month-long test deployment off Hanson Island in Johnstone Strait, BC, during the summer of 2002. This area is known for frequent killer whale sightings during the summer months. Manual inspection of each recorded sound file confirms this, with many days when killer whale vocalizations could be heard for more than 15 minutes per hour (Fig. 7(a)). A more surprising result is the number of false triggers associated with boat noise (Fig. 7(b)), suggesting that these boats generate significant noise in the frequency bands used by the killer whales and therefore used by our trigger circuit. Jet boat noise is especially difficult to discern from actual killer whale vocalizations because of the significant harmonics in the exact same frequency bands as the ones used by the whales. However, preliminary comparisons with nearby listening stations suggest that the monitoring system is capable of recording the presence of killer whales in the area, and in the more remote locations of the coast where we plan to locate these devices the number of all sorts of vessels is very limited, especially during the winter months.

The first such system is presently deployed off Langara Island (Table II) at the northern tip of the Queen Charlotte Islands to monitor for the presence of wintering resident killer whales.

	Two hydrophone towed array	**Shore base monitoring system "Orcabox"**	**Underwater deployable monitoring system (PATC)**
Frequency range	1-22.05 kHz	0.1-10 kHz (programmable)	0.05-1 kHz and 0.05-10.5 kHz (programmable)
Size	Electronics: 0.75 by 0.6 by 0.6 m. Winch: 1 by 0.9 by 1.2 m	1.5 by 0.5 by 0.5 m Solar panels: 1.3 by 0.6m	0.21 m diam. by 1.7 m long. Deployment depth to 1000m
Power consumption	Electronics: 90W Laptop: 70W Winch: 1500W	Idle mode: 1.5 W Recording: 7.5 W	Average power: 1.8 W
Disk capacity	Gbytes (computer hard disk)	20 Gbytes	24 Gbytes (expandable)
Deployment periods	Days, weeks. Duration of survey. Data backed up on CDs.	<12 months (batteries charged by solar cells. Disk space limited)	<12 months (depends on size of battery pack and number of hard disks installed)
Species recognition	Under development	Killer whale recognition circuit.	Killer whale recognition circuit (high freq. sampling). Low frequency sampling presently on timer.

Table I. System specifications for the three passive monitoring systems discussed in the text; a two hydrophone towed array, a shore based monitoring system called the "Orcabox", and a long- term underwater deployable monitoring system called "Passive Acoustic Tracking of Cetaceans" (PATC).

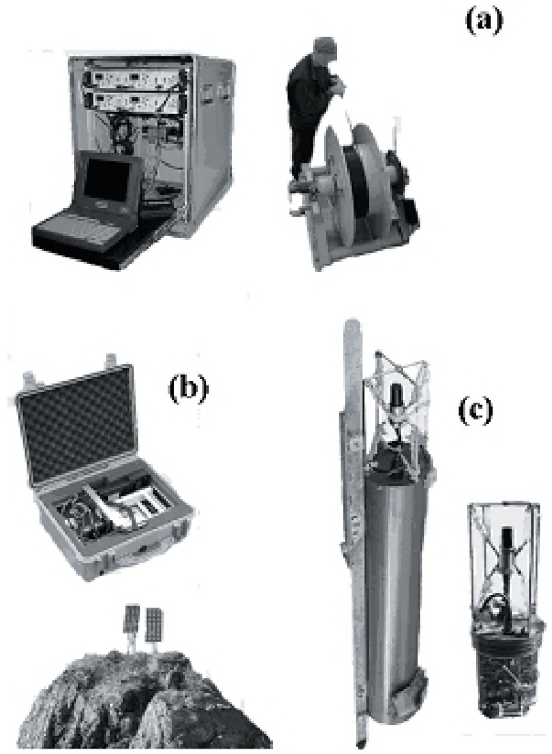

Figure 5: Photographs of the three different passive mammal-tracking systems discussed in the text. (a) The towed array consists of an armoured cable with two hydrophones connected to amplification, filtering units and a laptop computer where the signals are processed and recorded with GPS positions and time information. (b) A shore based battery powered system that uses solar panels to charge batteries. Shown are also two solar panels mounted on a local rock. (c) A self-contained battery operated recording package designed for offshore, submerged deployments, typically on deep moorings. The hydrophone and electronics are shown with and without the pressure housing which also contains the battery pack.

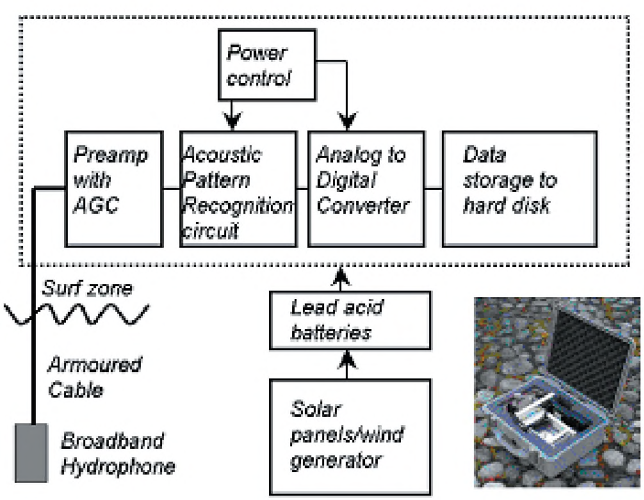

Figure 6. Schematic diagram showing the main components of the shore based acoustic monitoring system, or "Orcabox".

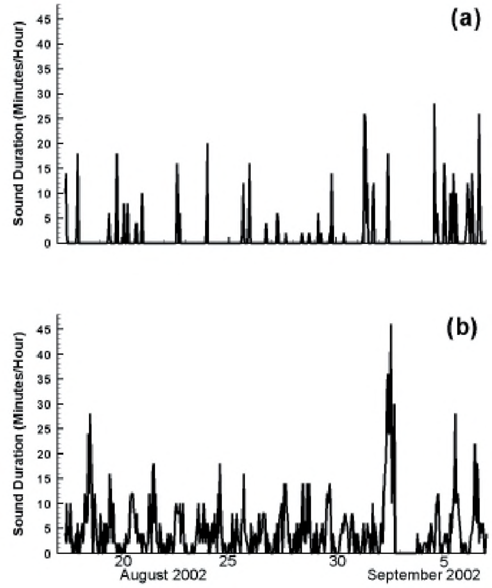

Figure 7. Results from Hanson Island, Johnstone Strait, showing the (a) the number of minutes per hour that killer whales were present, and (b) the significant time with boat noise.

3.2 Underwater deployable system

For offshore long-term monitoring or in areas where the water depth is more than a few hundred meters, it is necessary to use stand-alone self-contained instruments. A number of systems with a range of capabilities have been developed for a variety of applications by different groups over the years, including; "L-CHEAPO" (Worcester et al., 1995), "Haruphone" (Fox et al., 2001), "Pop-up" (Clark et al., 2002), "EARS Buoy" (Wright, 2003), and "ARP" (Munger et al., 2004; Wiggins et al., 2004).

To limit data storage and power requirements we wanted such a system to incorporate some limited artificial intelligence to minimize operation when no mammal signals are present. The passive acoustic tracking of cetaceans (PATC) instrument designed and built for this purpose is shown in Figure 5(c). A block diagram of the most significant components in this system is shown in Figure 8.

This instrument incorporates low-power components and is designed for deployment periods lasting up to 12 months and incorporates timing and vocalization recognition schemes as outlined below. The aluminium pressure housing has been designed for depths up to 400m, while the broad band (10-20000 Hz) hydrophones presently used (VEMCO) are certified only to 100 m. However, this hydrophone can easily be swapped for another hydrophone with better depth rating if so desired. The signal from the hydrophone is passed through the same amplifier and AGC circuit as used in the "Orcabox". From there on the design differs significantly from the previously discussed system.

Due to the requirement of the PATC instruments to record the low-frequency signals from the larger baleen whales such as the North Pacific right whale in addition to any killer whale calls, the system was designed as a hybrid system; recording at a lower 1000 Hz sampling rate (50-500 Hz bandwidth) during most of the time, while recording at 21000 Hz (50-10500 Hz bandwidth) in the presence of killer whales. When a reliable automated scheme to detect the larger whale calls becomes available, the design will be modified to automatically decide on the sampling scheme to use based on the type of animal call. Research is underway to develop such algorithms.

The signal from the AGC circuit is sent both to an analog acoustic pattern recognition circuit, equivalent to the one described earlier, and via a 500 Hz low-pass filter (LPF) directly to the analog to digital converter (A/D), which has programmable sampling rate. Most of the time the signal will be digitized at 1000 Hz (16 bits) for time periods controlled by a low-power CF1 microcontroller. However, if during these recording periods the acoustic pattern recognition circuit detects killer whale calls, the instrument automatically switches to a 10 kHz LPF and increases the sampling rate to 20000 Hz for a pre-programmed period before returning to the low-frequency sampling scheme. All data are time-stamped and stored on one of several 8Gbyte hard drives.

The frequency and length of the 1000 Hz sampling periods are determined prior to instrument deployment and are based on the duration of the deployment, the size of the battery pack and the available disk space. We have presently deployed two instruments with one hour recording periods followed by one hour of low-power sleep mode. Sixteen Gbytes have been reserved for the low-frequency sampling and 8 Gbytes are allocated for high frequency killer whale recordings. This arrangement is intentionally made quite flexible, making it easy to add or remove hard discs and added battery packs for different requirements.

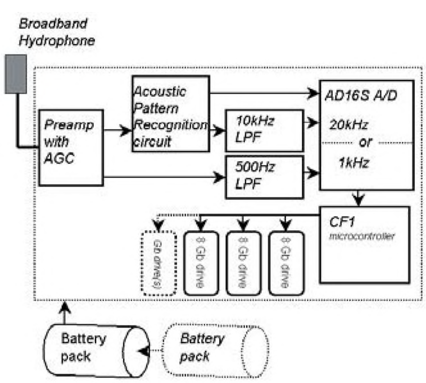

Figure 8. Schematic diagram showing the main components of the self-contained PATC instrument designed for offshore large baleen and killer whale monitoring.

With any automated recording scheme where the data recording is based on the fulfilment of certain predetermined conditions such as the acoustic pattern recognition circuit used here, it is important that the probability of false triggers is kept to a minimum. There will always be a possibility that a nearby noise source, such as parts of the mooring itself, will trigger the recording circuitry continuously or periodically and therefore fill up the disc space and drain the batteries prematurely. To eliminate this possibility we designed a recording scheme as outlined in Figure 9.

During a typical six month deployment the CF1 microcontroller will continuously repeat a 2 hour cycle: recording time stamped 500 Hz signal to hard disk for 1 hour; then going into a low power (6μA) mode for 1 hour. If during the recording periods the acoustic pattern recognition circuit detects killer whales in the area, the system will switch to the faster 20 kHz sampling and record a 10-minute section of data at this higher rate. However, before deployment the system has been allocated a fixed number of these recording periods per day and if the quota has been used up on a given day the system will not record. However, if the quota from one day was not used, this number of recording periods will be added to the quota for the next day to allow for more frequent sampling during some limited periods when killer whales might be in the area. If no killer whales are detected over a predetermined period (typically one week) the system has been programmed to record ambient noise to fill up part of the quota. These data will be used to investigate the ambient noise conditions in the instrument location and can also be used for environmental monitoring such as wind speed, rainfall, and overall shipping noise levels. This information might be useful in interpreting the vocalization data.

Even though the PATC instruments can easily be modified for bottom-mounted deployments, they are specifically designed to be deployed on moorings in deep water. In water depths of more than a couple of hundred meters there are several advantages to placing these monitoring devices higher up in the water column. The cost of components such as pressure housings, connectors and hydrophones increases significantly if the deployment depth is more than about 400m. Also, the sound speed profile in the water column is often such that there is a surface duct in the upper ocean in which the sound from vocalizing whales can travel much greater distances (Urick, 1983). This duct might be seasonal or only occur at certain times of the day or in certain locations. However, any instrument deployed below such a surface duct would be limited to vocalizations from a relatively small area above the instrument. The instruments presently deployed on the west coast of Canada have been placed at a depth of 60 m in water depths of 400 m and 2110 m respectively (Table II).

Clearly the deployment location and depth will depend on the objectives of the monitoring program. If the goal is to detect the presence of any marine mammals in an area as large as possible, which is the goal for us with respect to North Pacific right whales, the hydrophone should be placed in the sound channel. However, if the objective is to monitor a certain area for the presence or absence of mammals, deeper instruments might be preferable.

In the search for the North Pacific right whale, the optimum instrument locations have to be determined based

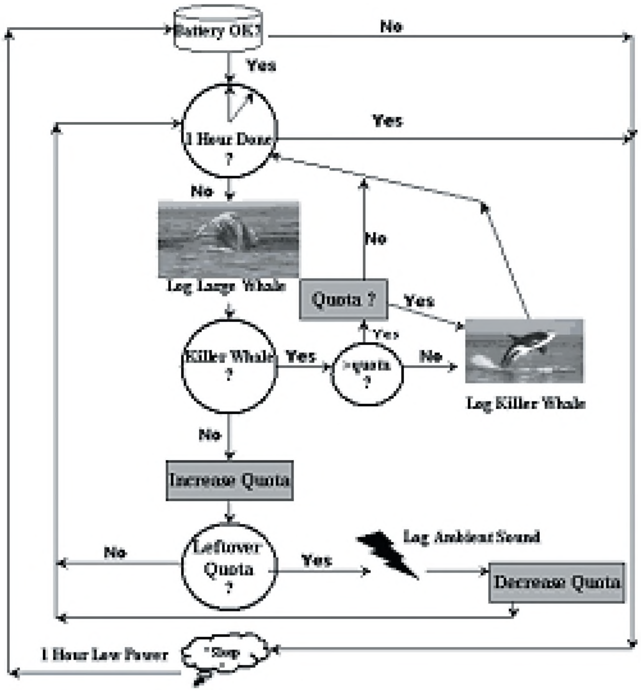

Figure 9. The recording scheme used in recent PATC deployments off the west coast of BC.

on historic sighting data. However, because these are few and far between, we based the initial instrument locations on survey data from other large baleen whales over the last number of years, assuming that the right whale will use the same feeding grounds if they are present.

Table II. Deployment information for the three instruments deployed during winter 2003/2004.

	"Orcabox"	PATC1	PATC2
Latitude	54 14.1N	50 57.5N	48 45.4N
Longitude	132 58.0W	129 59.6W	126 22.1W
Water depth	15m	2110m	400m
Hydrophone depth	15m	60m	60m

4 DATA INTERPRETATION

With the large data sets acquired by these systems comes the challenge of extracting species and in the case of killer whale vocalizations, matriline dialects in an efficient way. A quantitative measure of acoustic similarity is important to allow for species identification, or in particular cases determination of social groups or individual animals. Several approaches are presently being investigated as ways of detecting particular whale calls in sound recordings using both time-based and spectrogram-based techniques (see other papers in this issue). However, due to our initial interest in identifying different killer whale dialects and some familiarity with the neural network approach (Deecke and Ford, 1999) we chose this as a starting point for our evaluation of a suitable technique. We are presently just starting this work so the results presented below are by no means a complete investigation into the use of neural networks for species and dialect recognition.

4.1 Neural networks

Artificial neural networks were developed by modeling biological systems of information processing (Dasgupta, 1991; Hinton, 1992), and an artificial neuron is a processing element that takes an input vector, multiplies each element according to a series of weights, adds a bias term (possibly zero), and processes the result according to a transfer function (often a sigmoidal function) to produce a scalar output.

Neural networks are capable of performing well on noisy data, and on data where the underlying signal is unknown or difficult to differentiate from background data. However, the performance of the neural net relies on the availability of a large training set. A small training set can result in the net being unable to generalize to a larger data set. A lack of optimization techniques also requires testing many different sizes of nets, with different transfer functions, to obtain an optimal result.

The spectrograms used for training the neural networks are generated using the MATLAB signal processing toolbox, operating on the minimum number of data points that allow for visual differentiation of vocalization from noise (256 points sampled at 22050 Hz for the killer whale vocalizations), resulting in a 128 point complex vector.

Preliminary results suggest that fairly simple neural networks can be used to detect killer whale calls in the presence of boat noise as well as noise from breaking surface waves and that these results are in agreement with the results by Deecke and Ford (1999). However, further studies are required before real-time algorithms can be implemented into self-contained instruments.

5 CONCLUDING REMARKS

Recent concerns about the status of several whale species in Canadian waters is the driving force behind the work to establish an *in situ* and more long-term passive acoustic monitoring program on the west coast of Canada. Early results with the combined use of a towed array as well as land and offshore-based systems are encouraging. The use of passive acoustic monitoring is a non-intrusive approach to collecting the baseline data required for any successful recovery strategy.

The use of modern low-power electronics combined with powerful microcontrollers and readily available data storage are making long-term monitoring feasible. However, the collection of ever-larger data sets is highlighting the need for improved software to deal with the data. It is no longer feasible to hire a large number of graduate students to sit and listen through the data in real time to recognize a particular whale species, dialect or individual animal.

A number of different approaches are presently being investigated (e.g., Harland and Armstrong, 2004; Johansson and White, 2004; van Ijsselmuide and Beerens, 2004)see other articles in this issue) ranging from parametric modeling and neural networks to different spectrogram correlation techniques. We have been looking into using neural network routines on spectrograms as a tool to extract killer whale vocalizations in large audio files, and for this specific use we find that this approach is showing some promise. However, it remains to be seen whether this approach will work for the more demanding task of distinguishing between all the different clan dialects among the resident killer whales on the west coast. We also intend to investigate the ability of this approach to detect the distinct, but much lower frequency, North Pacific right whale calls.

When suitable vocalization recognition algorithms have been developed, the natural next step will be to implement these into smart instruments to be deployed in the field. This will result in reduced demands on data storage and power and reduce the amount of post-deployment processing that will be required. We envision a time when these instruments will send back species and clan information directly to the scientists via satellite phone. There will clearly always be need for storage of some raw data for post-processing, but it should be possible to significantly reduce this in the future.

The instruments discussed here record only information about sound pressure level as a function of time. With a single pressure hydrophone there is limited information about the actual location of any vocalizing mammal. A next step for us will be to incorporate a second vertical hydrophone to the systems. A vertical array will make it possible, in combination with some sound propagation modeling, to estimate the range to low-frequency large mammal vocalizations (Laplanche et al., 2004)see other articles in this issue). This should be a straightforward addition to the PATC instruments because they are already set up for multi-channel inputs. Direction to the calling whales can be obtained by the use of a horizontal array of acoustic monitoring devices and relative travel time (see other articles in this issue). Another approach would be to make use of Directional Fixing And Ranging (DIFAR) hydrophones (McDonald, 2004). With a DIFAR hydrophone, three signals will have to be monitored and digitized in the monitoring device in addition to the compass heading of the hydrophone. The three channels would be two orthogonal components of particle velocity and a signal from a separate pressure hydrophone, which is required to resolve directional ambiguity.

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7 REFERENCES

Barlow, J., and B.L. Taylor. 1998. Preliminary abundance of sperm whales in the northeastern temperate Pacific estimated from a combined visual and acoustic survey. Document number SC/50/CAWS20, Int. Whaling Commission, Cambridge.

Barrett-Lennard, L.G., J.K.B. Ford, and K.A. Heise. 1996. The mixed blessing of echolocation: differences in sonar use by fish-eating and mammal-eating killer whales. *Anim. Behav.* 51:553-565.

Benson A.J. and A.W. Trites. 2002. Ecological effects of regime shifts in the Bering Sea and eastern North Pacific Ocean. *Fish and fisheries.* 3:95-113.

Bigg, M.A., G.M. Ellis, J.K.B. Ford, and K.C. Balcomb, 1987, *Killer Whales: A Study of their Identification, Genealogoy and Natural History in British Columbia and Washington State.* Nanaimo, BC: Phantom Press.

Brownell R.L., P.J. Clapham, T. Miyashita, and T. Kasuya. 2001. Conservation status of North Pacific right whales. *J. Cetacean Res. Manage.* (Special issue) 2:269-286.

Clark, C.W., F. Borsani, and G. Notarbartolo-di-Sciara. 2002. Vocal activity of fin whales, Balaenoptera physalus, in the Ligurian Sea. *Mar Mamm. Sci.* 18:286-295.

Dasgupta, C. 1991. Neural networks: An overview. *J. Indian Inst. Sci.* 71: 491-502.

Deecke, V.B. and J.K.B. Ford. 1999. Quantifying complex patterns of bioacoustic variation: Use of neural network to compare killer whale (*Orcinus orca*) dialects. *J. Acoust. Soc. Am.* 105: 2499-2507.

Ford, J.K.B. 1989. Acoustic behaviour of resident killer whales (*Orcinus orca*) off Vancouver Island, British Columbia. *Can. J. Zool.* 67:725-745.

Ford, J.K.B. 1991. Vocal traditions among resident killer whales (*Orcinus orca*) in coastal waters of British Columbia. *Can. J. Zool.* 69:1454-1483.

Ford, J.K.B., G.M.Ellis, and K.C. Balcomb, 2000. Killer Whales: The Natural History and Genealogy of Orcinus orca in British Columbia and Washington, Second Edition, UBC Press, Vancouver and U. of Washington Press, Seattle, 102pp.

Fox, C.G., H. Matsumoto, and T.K.A. Lau. 2001. Monitoring Pacific Ocean seismicity from an autonomous hydrophone array. *J. Geophys. Res*. 106(B3):4183-4206.

Harland, E.J., and M. Armstrong, 2004, The real-time automated detection of calls of all cetacean species. Can. Acoust. Vol. 32, #2, June 2004.

Hinton, G.E. 1992. How neural networks learn from experience. *Sci. Am*. 268: 145-151.

Johansson, A.T., and P.R. White, 2004, A system for detection and identification of cetaceans by parametric modeling of whistle signals. Can. Acoust. Vol. 32, #2, June 2004.

Kenney, R.D. 2001. North Atlantic, North Pacific, and Southern right whales. pp. 806-813 in W.F. Perrin, B. Wursig, J.G.M. Thewissen, W.F. Perrin, B.G. Wursig (eds.), The Encyclopedia of Marine Mammals. 1414pp.

McDonald, M.A, 2004, Directional Fixing and Ranging (DIFAR) Hydrophone applications in whale research. Can. Acoust. Vol. 32, #2, June 2004.

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

Munger, L., M. McDonald, S. Moore, S. Wiggins, D.K. Mellinger, and J. Hildebrand, 2004, North Pacific right whales: long-term acoustic detection and localization in the Bering Sea. Can. Acoust. Vol. 32, #2, June 2004.

National Research Council, 2000, Marine Mammals and Low-Frequency Sound, National Academy Press, Washington, D.C., USA.

Roemmich D. and J. McGowan. 1995. Climate warming and the decline of zooplankton in the California current. *Science.* 267: 1324-1326.

Ross. P.S., G.M. Ellis, M.G. Ikonomou, L.G. Barrett-Lennard, and R.F. Addison, 2000. High PCB concentrations in free-ranging Pacific killer whales, *Orcinus orca*: effects of age, sex and dietary preference. *Mar Poll. Bulletin.* 40:504-515.

Rosenbaum, H.C., M.G. Egan, P.J. Clapham, R.L. Brownell, M.W. Brown. 2000. Utility of North Atlantic right whale museum specimens in assessing changes in genetic diversity. *Conserv. Biol.* 14:1837-1842.

Van Ijsselmuide, S.P., and S.P. Beerens, 2004, Detection and classification of MARINE MAMMALS using an LFAS system. Can. Acoust. Vol. 32, #2, June 2004.

Wiggins, S.M., M.A. McDonald, L.A. Munger, J.A. Hildebrand, and S.E. Moore, 2004, Waveguide propagation allows range estimates for North Pacific right whales in the Bering Sea, Can. Acoust. Vol. 32, #2, June 2004.

Worcester, P.F., K.R. Hardy, D. Horwitt, and D.A. Peckham. 1995. A deep ocean data recovery module. Proc. IEEE Oceans '95, pp. 1225-1231.

Wright, A.J. 2003. The Effects of a Tropical Storm on the Use of Clicks by Sperm Whales in the Northern Gulf of Mexico. Masters Thesis, Univ. Wales, Bangor.