Noise logger overview

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Contents

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This overview is meant as a limited service and internal working document to provide some background information on passive acoustic monitoring for our colleagues in the Caribbean, in a field undergoing rapid technological development. It contains extended excerpts of text and data copied from and previously published by other authors, most often without further indication of the individual citations; above all these publications are:

- Mellinger D.K., Stafford K.M., Moore S.E., Dziak R.P. and Matsumoto H. (2007). An overview of fixed passive acoustic observation methods for cetaceans, Oceanography 20 (4): 36–45.
- Dudzinksi K., Gitter S., Lammers M., Lucke K., Mann D., Simard P., Wall C., Rasmussen M., Magnúsdóttir E. E., Tougaard J. and Eriksen N. (2011). Trouble-shooting deployment and recovery options for various stationary passive acoustic monitoring devices in both shallow and deep water applications. Journal of the Acoustical Society of America, 129(1): 436-448.
- Zimmer, W.M.X. (2011). Passive acoustic monitoring of cetaceans. Cambridge University Press.
- Sousa-Lima R.S., Norris T.F., Oswald J.N, Fernandes D.P. (2013a). A Review and Inventory of Fixed Autonomous Recorders for Passive Acoustic Monitoring of Marine Mammals. Aquatic Mammals, 39(1): 23-53, DOI 10.1578/AM.39.1.2013.23
- Sousa-Lima R.S., Norris T.F., Oswald J.N., Fernandes D.P. (2013b). Errata – A Review and Inventory of Fixed Autonomous Recorders for Passive Acoustic Monitoring of Marine Mammals. Aquatic Mammals, 39(1): 23-53, DOI 10.1578/AM.39.1.2013.23

Please refer to the original publications for more information.

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1 Introduction

The human perception of the underwater world is one of a mainly quiet environment. With a variety of biotic and abiotic sound sources present in the seas this of course is a misconception based on our lack of sensitivity to underwater acoustic signals. Our human hearing is tuned to receive and perceive sounds in air; the physical conditions are completely different underwater which makes us insensitive to sounds underwater. In fact the ocean is a naturally noisy environment with naturally-occurring ambient noise that can be generated by abiotic sources (wave action, wind across the sea surface, tidal or storm surges, seismic events, and underwater currents), as well as biotic sources (i.e. animals such as shrimp and other crustaceans, fish, seals and cetaceans communicating or echolocating - and many more). At the same time, the human use of the oceans has steadily increased over the past decades. This goes along with the emission of sound into the oceans, either intentionally e.g. to investigate the ground for potential hydrocarbon deposits or unintentionally as a mere by-product of e.g. shipping. Due to a constant increase in human use of the ocean anthropogenic noise is increasingly adding to this underwater sound scape. The most prominent anthropogenic sound sources are shipping, construction activities, seismic surveys, sonar and underwater explosions.

Marine mammals and especially cetaceans have not only adapted their lifestyle to the aquatic environment but also modified their main mode of interacting with this environment. This means, they adapted to an environment where light attenuates rapidly, but sound propagates well over long distances (Clausen et al. 2010). Active and passive use of sound therefore plays an important role for cetaceans in foraging, predator avoidance, navigation and communication (Au 1993). Thus, their life is almost entirely based on acoustic interactions with each other as well as with their environment.

In our attempt to monitor the presence of marine mammals, especially cetaceans, their acoustic activity opens the opportunity for us to eavesdrop and to study their behaviour passively through listening and detecting their sounds and vocalisations. This overview of underwater sound recording systems which can be used to study the life of the mainly cryptic marine mammal species is intended to facilitate researchers, potential funding bodies and finally regulators with information on the potential of this technique, its limitations and most importantly with technical details and a market overview. This is only meant as an internal working document. It is based on a number of peer-reviewed publications as well as direct consultation with manufacturers and experiences of researchers using the devices in the field. This overview is focussed in its research applications to the study of marine mammals in the Caribbean waters (deploying or using such devices in other, e.g. polar waters might result in a different choice of preferred device). Besides technical information on the sound recording systems this overview comprises a general introduction to passive acoustic monitoring as well as to marine mammal sounds, but it is not intended to provide information on the software for detection of vocalizations, statistical methods, and interpretation of results. This work took place as part of the Wageningen University BO research program (BO-11-011.05-005) and was financed by the Ministry of Economic Affairs (EZ) under project number 4308701036.

2 Passive Acoustic Monitoring (PAM)

What we call 'sound' is the perception of a pressure change in a medium (for us humans usually in air, for the marine mammals predominantly underwater) – the conversions is either performed in the inner ear in living subjects or in a hydrophone as part of the underwater sound recording system. In a sound recorder (logger) the pressure is converted into voltages which are amplified, filtered and then digitised for recording onto memory storage.

Passive acoustic survey methods comprise fixed as well as mobile acoustic sensors. Hydrophones may be towed behind a ship or affixed to an ocean glider or other mobile platform to sample a large area. Alternatively, the hydrophone instruments may be left in place for long time periods. Advantages of the mobile approach include large areal coverage and simplicity in combining acoustic detection with a visual survey, while the principal advantages of the fixed approach are that observation usually spans a longer time period and is frequently less expensive. This review is focussed on the fixed systems.

Fixed passive acoustic surveys require several steps, including survey design, placement and sometimes recovery of recording instruments, extraction of vocalizations of interest from recorded data, statistical analysis of vocalizations, and interpretation of the results.

Two types of passive acoustic equipment are used widely for capturing sound—cabled hydrophones and autonomous recorders. Cabled hydrophones are typically deployed in permanent or semi-permanent installations. Because of the expense of cabled systems, they are in widespread use mainly by navies or other governmental agencies; examples include the Sound Surveillance System of the US Navy; the hydrophone arrays on US Navy test ranges in the Bahamas, southern California, and Hawaii; and the hydrophones of the Comprehensive Test Ban Treaty Organization. The benefits of these systems for scientific research are that they provide data continuously in near-real time (so that rapid response to unusual events is possible), they have hydrophones in pelagic areas where marine mammal surveys are otherwise rare, and their operation and maintenance is funded by external sources.

However, these systems typically have access restrictions because of their military or sensitive nature, so that the data are not easily accessible. Further, the recording bandwidth is often restricted to fairly low frequencies due to the nature of the signals for which they were designed. Cabled systems operated by nongovernmental organizations often consist of one or a few hydrophones placed within several kilometres of shore. Their data are more openly accessible but typically cover only relatively small shelf areas. The advent of cabled ocean observatories (e.g., Barnes et al., 2007; Andre et al. 2011) promises to extend the capabilities of such non-military systems to larger offshore areas.

Autonomous recorders consist of a hydrophone and a battery-powered data-recording system. These instruments are usually moored on the seafloor, sometimes with a cable and flotation to buoy the hydrophone sensor up in the water column (e.g., at the depth of the deep sound channel) for periods of up to two years. Depending on the instrument configuration and deployment duration, sound capture happens either continuously or according to a sampling plan. Autonomous hydrophones are typically deployed in arrays of three to ten instruments to provide areal coverage and to allow for localization of sound sources. A number of laboratories have designed and used such instruments since the mid-1990s (Calupca et al., 2000; Fox et al., 2001; Wiggins, 2003), and more recently a larger number of commercial version has become available (see table 1).

These instruments store acoustic data internally, so they must be recovered before data analysis can begin. In addition to the widely used cabled hydrophones and autonomous recorders, radio-linked hydrophones are occasionally used for marine mammal acoustic surveys. These combine a hydrophone sensor on a mooring (Clark et al., 2007) or on shore-fast ice (Clark et al., 1996) with a radio link to a shore station or ship (e.g., Rankin et al., 2005). As with cabled systems, data are captured continuously in real time. A final variant consists of using marine mammals themselves as platforms for acoustic sensors. By miniaturizing the sensor and electronics package to fit into an attachable tag, the instrument can record acoustic data from areas where the animal itself is exposed. Such tags have been deployed on larger marine mammals, including elephant seals (Mirounga angustirostris; Fletcher et al., 1996; Burgess et al., 1998) and several species of mysticete and odontocete whales (Madsen et al., 2002a; Johnson and Tyack, 2003).

A key difference in choice of instrumentation is whether hydrophones are deployed in isolation from one another, in distributed small-area arrays for localization, or in large coherent arrays to allow beamforming. When just listening to underwater sound or marine mammal vocalisations in a particular area (e.g. in a public display) a single sensor (a listening station) is sufficient. Also, when several single sensors are placed tens to hundreds of kilometres apart, they are usually too far apart to detect an individual animal on multiple instruments, so this configuration may be considered to be multiple isolated instruments. When instruments are placed closely enough that three or more can detect a vocalizing animal, the animal can be located using time-of-arrival differences; localization of successive vocalizations allows the individual to be tracked as it moves (Clark et al., 1996). When approximately 10 or more hydrophones are deployed in a tightly spaced array, a sound wave from an animal arrives coherently at all of the hydrophones, allowing beamforming techniques to be used (Johnson and Dudgeon, 1993; Stafford et al., 1998). Beamforming increases the signal-to-noise ratio (SNR) of sound arriving from certain directions and hence its detectability.

3 Detection parameters

When attempting to monitor the presence of marine mammals we have to deal with a variety of aspects, all of them influencing our capability to detect the presence of the animal or identifying the species based on their sound emissions in the presence of other sounds.

In the context of passive acoustic monitoring, sound - while being neutral otherwise - is composed of signals (the wanted sound), noise and interference (the unwanted sounds). Acoustic interference is caused by sounds similar enough to the signals of interest (i.e. animal borne sounds) to degrade our ability to detect those signals. In the context of passive acoustic detection of cetaceans it may be possible that even sounds of other marine mammals have to be considered as interference, e.g. when listening for beaked whales a dolphin echolocation signal (click) might resembles the click of a beaked whale (Zimmer 2011).

Underwater 'noise' is sum of all randomly occurring, varying sound at a specific location and given point in time. The noisier an environment is, the harder it might become to detect the presence of a cetacean by means of passive acoustic monitoring.

The acoustic properties of the communication signals of marine mammals can vary widely – from short pulses to stereotyped whistles to complex songs. However, in order to be useful for communication a signal must also be complex enough to allow encoding the information. A continuous signal with continuous frequency and amplitude e.g. would only convey information on the animal's presence. Even though the amount of information encoded in communication signals of marine mammals is widely unknown (except for stereotypic signature whistles) it can be assumed that the information content is be context specific and will vary with the behavioural state of the sender.

A complication for detecting signals emitted from marine mammals is that the type and occurrence of communication signals from marine mammals is unpredictable. Especially when communication in a noisy environment or over long distances, marine mammals may have to change their signalling strategy: they can increase the complexity of their signals to achieve sufficient redundancy in transmission of the information to the receiver or they could slow down the information rate and transmit very simple signals over long periods of time to reduce the required bandwidth of the communication channel (Zimmer 2011).

Besides considering the detection parameters, knowledge of the acoustic emissions of the marine mammal species targeted when using PAM to detect them is the key-information needed in order to choose the best system and the right deployment design. When multiple species are targeted the optimum solution will logically have to be a compromise to cover and allow detecting as many of the acoustic features of the marine mammal vocalisations as possible.

4 Marine mammal sounds[1]

Generally, sounds of baleen whales (all whale species of the taxonomic sub-order of ‘mysticeti’) are very different from those of toothed whales (sub-order: ‘odontoceti’), with a wide range of types and quantity of signal types across mysticete species. Following Wartzok & Ketten (1999) acoustic signals emitted by mysticetes can be characterized as low frequency moans (0.4-40 sec; fundamental frequency well below 200 Hz), simple calls (impulsive, narrow band, peak frequency <1 kHz), complex calls (broadband, amplitude-modulated (AM) or frequency-modulated (FM) signals) and complex ‘songs’ with seasonal variations in phrasing and spectra (Watkins 1981; Payne et al. 1983). Infrasonic Signals, typically in the 10- to 16-Hz range, are well documented in at least two species, the blue whale (*Balaenoptera musculus*) (Cummings and Thompson 1971), and the fin whale (*Balaenoptera physalus*) (Watkins 1981; Watkins et al., 1987).

Even though a specific sound has only rarely been associated with a given behavioural event it is proposed that mysticete sounds serve social functions including long-range contact, assembly calls, sexual advertisement, greeting, spacing, threat, and individual identification (Dudzinski et al. 2009); It is probable that sounds produced by mysticetes serve to synchronize biological or behavioural activities in listeners that promote subsequent feeding or breeding.

Wartzok & Ketten (1999) provide also a classification for sounds produced by odontocetes, categorising them into species-stereotypic broadband clicks with peak energy between 10 and 200 kHz, individually variable burst pulse click trains, and constant frequency (CF) or frequency modulated (FM) whistles ranging from 4 to 16 kHz. Ultrasonic signals are highly species specific and have been recorded from 21 species, but all odondotcete species are believed to be echolocators. These echolocation signals (‘clicks’) are short pulsed signals which can have a broad bandwidth as e.g. in the killer whale (*Orcinus orca*), or of narrow-band composition as in the harbour porpoise (*Phocoena phocoena*). Odontocetes use echolocation for foraging, orientation and obstacle and/or predator avoidance (Au 1993; Tyack and Clark 2000; Morisaka and Connor 2007). Echolocation signals are usually highly directional and the echoes returning from ensonified objects provide information on the distance to the object as well as information on the angle (both in azimuth and elevation) at which it is positioned. Clicks are emitted at varying repetition rates; When searching or trying to orient over larger ranges animal emit clicks at a slow succession rate while rates of >1.000 clicks per second can be generated when investigating an object at close range.

The high-repetition, burst-pulsed sounds can also have social functions. In non-whistling species as the harbour porpoise they are the only proven type of active communication signal (Clausen et al. 2010). Sperm whales, which also only produce clicks, are an exception in this context as they have dedicated click types with different source properties for echolocation and communication (‘codas’; Madsen et al. 2002a, b).

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1 Useful information on underwater acoustics in general as well as the use of sound by marine mammals in particular can be found at the DOSITS website: http://www.dosits.org/ or in Richardson et al. 1995.

Narrow-band tonal sounds are continuous signals called signature whistles (Caldwell and Caldwell 1965, 1990; Tyack 1986; Sayigh et al. 1990). These signals are usually highly stereotypic and serve for identification of individual animals.

The sounds produced by pinnipeds are typically frequency modulated or pulsed sounds. Except for male walruses, pinnipeds do not whistle (Dudzinski et al. 2009). Pinniped vocalisation is strongly correlated with mating and the medium (under water or on land). While phocid seals tend to be more vocal under water (especially the true seals that mate under water) otariid seals are much more vocal on land.

4.1 Behavioural Considerations

Some species are more amenable to accurate acoustic surveys than others. Species-specific factors influencing fixed passive acoustic surveys include these:

- Frequency

Sounds below 1 kHz have significantly less seawater absorption loss than sounds above 10 kHz (François and Garrison, 1982), and thus can be detected at greater distances. The former frequencies are typical of mysticetes, while the latter are typical of odontocetes. Figure 1 shows the frequency ranges of cetacean vocalizations.

- Vocal behaviour

Some cetaceans vocalize more frequently or more consistently than others, making them better subjects for acoustic surveys. Vocalizing behaviour varies with gender, age, and season. For instance, adult males of many baleen whale species vocalize regularly and loudly during the breeding season.

- Source level.

The larger cetaceans, including mysticete whales and sperm whales, produce intense vocalizations that can be detected at distances of several tens of kilometres on a single hydrophone (Barlow and Taylor, 2005) and much farther—hundreds of kilometres—on hydrophone arrays (Clark, 1995). For instance, blue whale (*Balaenoptera musculus*) tonal calls have been measured over 185 dB RMS re 1 μPa @1 m (Cummings and Thompson, 1971; McDonald et al., 2001; Thode et al., 2000; Širović et al., 2007), while on-axis sperm whale clicks have been measured at instantaneous levels up to 223 dB re 1 μPa peak equivalent RMS @ 1 m (Møhl et al., 2000). In contrast, bottlenose dolphin (*Tursiops truncatus*) tonal sounds (whistles) have been measured at source levels up to 169 dB re 1 μPa RMS @ 1 m (Janik, 2000), while their clicks have been measured at 210–213 dB re 1 μPa RMS @ 1 m (Au et al., 1986).

- Directionality

High-frequency click sounds of some odontocetes are highly directional. For instance, the directionality index for bottlenose dolphins is at least 26 dB (Au, 1993), and sperm whale sound emission is at least 35 dB louder in some directions than others (Møhl et al., 2000). In contrast, low-frequency baleen whale sounds are believed to be emitted essentially omnidirectionally, in part because the long wavelengths make directional sound emission all but impossible.

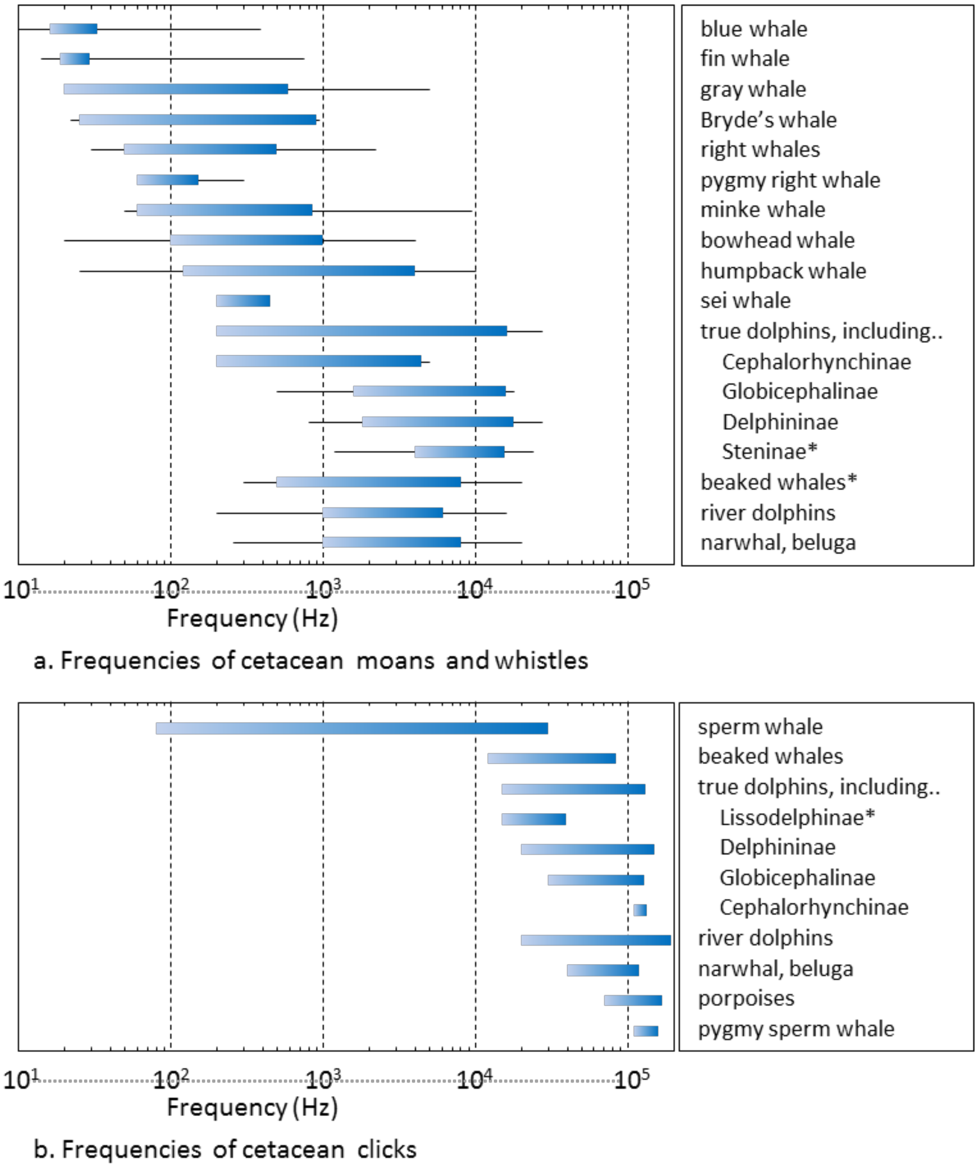

Figure 1. Known frequency ranges of cetacean sounds. Large whales are listed by species, while toothed whales are grouped into families. The thick bar shows the range of the most common types of vocalizations, while the thinner line shows recorded extremes of frequency. An asterisk (*) indicates that the upper frequency is unknown because of recording equipment limitations. (a) Tonal sounds—moans and whistles—with most baleen whale species shown separately. (b) Echolocation clicks. Baleen whales do not produce high-frequency echolocation clicks, while some toothed whales, dolphins, and porpoises do not produce tonal sounds (Graphs taken from Mellinger et al., 2007).

Vocalizations of a target species can be detected manually, with specialists listening to sounds and/or looking at spectrograms to find occurrences of these species' vocalizations (Clark et al., 1996; Stafford et al., 1999, 2001). The volumes of data involved, however, more often dictate using automatic detection.

Many methods for detection and classification have been developed and tested. Whatever the method used, two issues are paramount. The first is determining the type(s) of vocalizations to be detected and the amount of variability in these vocalizations. Some species, such as populations of fin whales (*B.*

physalus), have highly stereotyped vocalizations. Other species, such as common dolphins (*Delphinus delphis*), produce highly variable tonal sounds (Oswald et al., 2004). Other species produce sounds with intermediate levels of variability. Depending on the level of variability different detection methods and species classification techniques have to be applied.

The second issue is the desired accuracy of detection. In a perfect world, a detection method would find all instances of a certain call type, and nothing more. This ideal is never met, in part because there are inevitably faint calls that are difficult to classify, even by the best human specialists. The issue then becomes one of configuring the detector's sensitivity, or threshold, to achieve a certain trade-off between missed calls (false negatives) and wrong detections (false positives).

5 Applications and Analytical Methods

5.1 Determining Range and Seasonality

Acoustic surveys have been used many times to measure the range and seasonal occurrence of cetaceans. One advantage of fixed passive acoustic methods is that they can be performed year round at relatively low cost (e.g., Thompson and Friedl, 1982). Also, they can be carried out in remote areas that are difficult to survey other ways, such as far from land (Clark, 1995; Stafford et al., 1999; Nieukirk et al., 2004), polar regions (Širović et al., 2004, 2007; Munger et al., 2005; Moore et al., 2006; Stafford et al., 2007), or where weather is poor, and visual surveys impossible, in some seasons (Mellinger et al., 2007). In such studies, the number of vocalizations in each time period (e.g., each day, each month, each ten-day period) is counted, providing a rough indication of the number of animals in an area (e.g., Širović et al., 2004).

Another method is to measure the amount of energy in the frequency band of the vocalization type, correct it for background noise level, and use that as an indication of the number of calls (e.g., Burtenshaw et al., 2004). Unfortunately, the connection between the number of vocalizations and the number of animals is tenuous at best; sometimes a single animal produces a rapid sequence of vocalizations in a short time, sometimes only an occasional sound. To correct for these behavioral differences, many studies have assessed the number of hours (or number of days) that contain at least one vocalization; this method greatly reduces the bias of a rapidly vocalizing individual, because one vocalization in a given time period has as much weight as many in that period. However, this method also effectively ignores multiple individuals vocalizing in the same time period, so it is better suited for surveys of relatively rare species, such as blue or right whales, than relatively common ones, such as fin whales or common dolphins. In any case, these methods provide at best an index of occurrence, and are perhaps best employed to determine when throughout the year a given species is present in an area (see, e.g., Clark, 1995; Mellinger et al., 2004a,b; Munger et al., 2005).

5.2 Abundance

Using a set of detected vocalizations to estimate the abundance of a species in a given area may be done in several ways. One is to derive the probability of detection as a function of range. This probability density function (PDF) may then be inverted using point-transect statistical methods (Buckland et al., 2001), which essentially extrapolate from the number of animals detected near the sensor to the number of animals present and vocalizing in some larger area. The PDF can be estimated either by (1) acoustically locating the animals, such as recordings from multiple hydrophones and using time-of-arrival differences to estimate position (Cummings et al., 1964), (2) estimating range to a vocal animal using acoustic multipath propagation effects (Cato, 1998; McDonald and Fox, 1999; McDonald and Moore, 2002; Širovic et al., 2007), or (3) using acoustic propagation models and distributions of source levels to estimate range from received levels (Cato, 1991). Point-transect sampling requires behavioural information on rates of animal movement through the monitored area to avoid double counting of individuals. Nearly all of these methods require acoustic estimation of group size, a field of study still in its infancy. Although many species have different vocal behaviour in the presence of different numbers of conspecifics (e.g., Parks et al., 2005), the relationship between vocal behaviour and group size is rarely hard and fast, and the consequent errors in abundance estimates can be large. A second general approach relies on cue-counting statistical techniques. Here the total number of vocalizations— “cues”— is combined with an estimate of the average cue rate per animal per unit time to estimate the number of animals detected (Buckland et al., 2001). This figure is then extrapolated to estimate the number of animals in the study area. This method requires detailed behavioural information on the rate of cue production, and for most species little information is available.

To estimate density or abundance in a given area using fixed instruments, instrument positions should be chosen without any bias toward any part of the area. This can be done by random positioning of individual instruments or by positioning a regular grid of instruments with a randomly chosen origin.

5.3 Technical aspects of PAM systems

The frequency range of the recordings is dictated by the sampling frequency (as a rule of thumb: sampling frequency/2 = frequency range of recording). With the maximum storage capacity, the frequency range of the sounds (species) looked for in mind, the ideal compromise between deployment duration the ideal sampling rate and/or sampling schedule ("duty cycle") can to be defined. However, signal processing theory dictates that the sampling frequency must be at least 2x highest frequency of interest. Thus, acoustic recording can generate huge volumes of data for marine mammals (see figure 2).

Sample Rate	Number Channels	Species / System	/Second	/ hour	/ day	/30 days	/year
1Hz	4	SMRU tag	8 B	28 kB	675 kB	19 MB	241 MB
250Hz	1	CTBT	500 B	1.7 MB	41 MB	1.2 GB	15 GB
1kHz	1	Baleen	1.9 kB	6.9 MB	165 MB	4.8 GB	59 GB
48kHz	1	Large odontocetes	94 kB	330 MB	7.7 GB	232 GB	2.8 TB
48kHz	2	Large odontocetes	188 kB	660 MB	15.4 GB	463 GB	5.5 TB
100kHz	1	Small odontocetes	195 kB	687 MB	16.1 GB	483 GB	5.7 TB
500kHz	2	SCANS / IFAW Porpoise	1.9 MB	6.7 GB	161 GB	4.7 TB	57.4 TB

Figure 2: Data volume created by underwater sound recording systems using various sampling rates. Examples given are for various recording systems and/or species. Colour code indicates the amount of data generated (blue: low to red: high). (Taken from Doug Gillespie: Fundamentals of PAM, presentation at University of St. Andrews, U.K.)

The ideal noise logger would have the following qualities:

High frequency range: hydrophones must have a wide frequency range, for recording marine mammals ideally ranging from the very low frequencies of baleen whales (down to 5 Hz = infrasound) to ultrasonic frequencies (preferably 100 kHz and more) to cover the frequency band of dolphin echolocation clicks.

Low self-noise: The voltage produced by the internal electronic circuits should be as low as possible to provide a maximum signal-to-noise ratio for the detected external signals.

High dynamic range: The digital resolution (in bits) of the recording system defines the resolution of the recorded sounds; at least 16 bit resolution should be provided.

High acoustic sensitivity: The receiving hydrophones should be very sensitive to allow for detecting sounds of low acoustic intensity. Hydrophone sensitivity is usually given in negative dB re 1V/µPa; the smaller this negative value is the more sensitive the hydrophone is (e.g. -200 dB re 1V/ µPa is less sensitive than -160 dB re 1V/µPa). The more sensitive a hydrophone is the less amplification is needed; this can save battery power[2] and increases the signal-to-noise ratio as the internal electrical noise would otherwise also be amplified.

Low power consumption: the lower the power consumption of the recording system (in all functional states: recording vs. idle) the longer the battery life and hence the possible recording duration.

Large data storage: This increases either the recording duration, the frequency range or the data resolution (e.g. 16 vs. 24 bit) of the recordings.

Smart sampling: The system should have an event logger and allow for smart sampling, i.e.:

I. switch to an pre-set recording mode if certain thresholds (received level at certain frequencies e.g.) is exceeded ('event'). Usually the frequency range of the recording would be increased or to record an acoustic event of special interest (such as the detection of a whale song or click), or

II. if intense acoustic events which might lead to overloading the system are to be avoided, the gain settings of the system might have to be adapted.

A buffer of several seconds should be implemented so that the sequence preceding the event can also be analysed in greater detail.

5.4 Research objectives

The general aims of research including the use of PAM devices are:

- Detect presence of marine mammals in the Wider Caribbean waters (over wide range of spatial and temporal scales)
- Define habitat use
- Assess effect of anthropogenic activities on (vocally active) marine mammals

The design of a passive acoustic surveys and equipment have to be decided upon to fit the particular study or question. Factors important in design include: length of the study, intended subject – noise or animal, frequency range of intended sound source, depth at the study site and whether localization of sound sources is necessary (Dudzinski et al. 2011).

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2 'Unfortunately', high sensitivity hydrophones generally have a built-in preamplifier which requires DC power.

5.5 PAM studies in the Caribbean

Passive acoustic monitoring (PAM) offers the opportunity to document acoustic activity from naturally occurring sources, biologic and physical, and anthropogenic sources in an identified study area with the least amount of direct labour and greatest degree of safety to human observers and underwater organisms. That is, passive acoustic gear can be deployed for several days, months or even perpetually with minimum human intervention, except when data are ready to be retrieved and analysed. PAM provides a valuable tool for documenting baseline ambient noise levels, presence of specific species in a given area of concern, vocal behaviour of species in a given study area, species distribution, habitat use, migration or interaction between individuals and groups in an identified geographic area, and as a mitigation tool especially in seismic surveys and anthropogenic noise assessment (Mellinger et al. 2007). A particular advantage over observations or measurements involving human operators/observers is the possibility to obtain long data series from remote areas and during periods where weather or other conditions makes it unsafe or impossible for observers to operate (Dudzinski et al. 2011). In order to study marine mammals in Caribbean waters passive acoustic monitoring offers a wide range of opportunities. The aim of using PAM is to monitor marine mammals and/or to study ambient ocean noise over long periods in various marine environments. PAM is used to avoid the requirement of large operational human and material resources for deployment and recovery of the recording devices.

Passive acoustic monitoring encompasses a suite of "listening" tools that can answer scientific questions and influence marine management and/or mitigation applications over spatial scales ranging from $<1km^2$ to regions and ocean basins.

The tools that are available to acquire and analyse underwater sound data have undergone a revolutionary change over the last decade, and have substantially increased our abilities to both collect and apply acoustics to marine conservation questions (Van Parijs et al. 2009). Different strategies can be employed in order to detect the vocal of echolocation signals of cetaceans, static acoustic detectors such as noise loggers or click detectors (for echolocating species, i.e. toothed whales) and towed hydrophones used on mobile platform such as survey vessels. These techniques allow to detect the presence of a cetacean, to identify the species and in ideally also to conclude on the number of calling animals.

While acoustic recording equipment can be stationary or mobile, the focus of this paper relates to the subset of PAM devices that are moored or secured in one place. Stationary configurations include standard moorings (via buoy or anchor) or cabled systems. The anchored unit is diver recovered, acoustically triggered to surface, or programmed to return to the surface after a set time (Mellinger et al. 2007). Recording devices are either operated manually or operate autonomously. Autonomous audio recording devices represent the majority of PAM systems. Most autonomous recording devices can record continuously or be set on a fixed duty-cycle, depending on the frequency band of interest to a study and the duration of a particular deployment (i.e., time at sea recording).

PAM devices can be used for recording sounds from low frequency baleen whales up to high frequency dolphin clicks and all sounds in between such as other marine mammals, fish and anthropogenic sources (ships, sonar, seismic exploration etc.).

6 Technical overview

6.1 System categorisation

Following a nomenclature suggested by Sousa-Lima et al. (2013 a, b) PAM systems can be divided into three main categories:

- Autonomous recorders (ARs)
- Radio-linked hydrophones (RLHs)
- Fixed cabled hydrophones (FCHs)

6.2 Autonomous recorders (AR)

These are self-contained systems in terms of their power supply and data storage which archive the recorded data. In order to download the data the devices have to be retrieved. They are typically designed to be semi-permanent deployed underwater with or without a surface expression (i.e. buoy). Several autonomous PAM devices are currently available that vary in size, shape, configuration and acoustic specification. All systems have at least one hydrophone and some systems have additional sensors for environmental variables (temperature, current, light etc.). Many systems record sounds directly to disk or memory of the unit (or relayed to land via satellite) but other more specialized systems record only certain characteristics of the sounds. Recordings are either constant or follow a duty-cycle, and the unit is left to run remotely until either the batteries or disk space is exhausted. The choice of model depends upon the study's design or question as each model has different benefits for particular situations. Aspects to consider when choosing an AR system are:

- Number of hydrophones vs. the available data storage and power supply
- Sampling frequency vs. recording time
- Recording setting vs. data storage and power supply
- Deployment duration vs. sampling scheme (duty cycle)

Deployment methods

Stationary configurations include standard moorings (via buoy or anchor) or cabled systems. The anchored unit can be diver recovered or lifted up by a ship-mounted crane, acoustically triggered to surface, or programmed to return to the surface after a set time. Autonomous PAM units generally require recovery after the allotted deployment period as data are often saved to an internal storage drive and must be extracted prior to analysis (Dudzinski et al. 2011).

Anchoring

Several key issues influence choice and design of mooring and these must be identified before deployment, which include bottom substrate, depth, associated tidal flux and current, prevailing weather conditions, local fisheries, ship traffic, study objectives and equipment selection.

Bottom substrate type: Anchoring on hard sea floors is more demanding than on soft bottoms; however, very soft substrates (e.g., sand or mud) call for caution to prevent critical components of the setup (such as data loggers and acoustic releases) from becoming buried.

Water depth and tide: If a surface float is attached to a bottom-mounted PAM unit, then the line connecting the anchor with the surface marker must be significantly longer than water depth at highest tide, to prevent the unit from being lifted off the bottom by current or waves. The depth at which any

PAM unit is placed might affect the type and amount of data collected; experience has shown that porpoise detections differ with depth of the data logger (e.g., Kyhn et al. 2008). Also, if a device is deployed near the water surface, its detector could be saturated by cavitation noise from braking waves, which could result in a prematurely-filled memory card. Thus, caution regarding unit placement can effect deployment time and the rate of false detections. However, conditions differ between locations and no general correlation between deployment depth and performance has been found.

Currents and weather: Equipment strength and weight is dependent upon sea conditions, with heavier equipment needed in areas with rough seas or greater depths.

Local Fisheries: Any trawling in a deployment area has the potential to lead to conflict. Best solutions are identifying a deployed buoy by large markers, equipped with radar reflectors and light, always in combination with announcement of the deployment positions to fishermen working in the area.

Ship traffic: Even if there is no trawling in a deployment area, high levels of both commercial and leisure vessel traffic can put equipment at risk. The same solutions outlined for potential fishery interaction are recommended to alert future ship traffic to the presence of PAM units.

Deployment time: Whenever equipment is deployed for periods greater than one week, the potential wear to all components must be considered. Possibility of wear should be considered whenever rope is used; thimbles might be needed to protect connections and for long time deployments, the use of wires or chains should be considered. When deploying in salt water, the risk of galvanic corrosion can be significant and extremely aggressive leading to failure of metal parts within days in extreme situations. All connections (shackles, thimbles etc.) should be made of high-grade stainless steel[3]. Iron should be galvanized or protected by sacrificial anodes of zinc and always be of oversize dimensions to allow for considerable loss of material due to wear and corrosion. This is particularly important for chains. Other metals should be avoided when possible (Dudzinski et al. 2011).

Release mechanism/ Retrieval methods

- Mechanical lifting of entire system (device + anchor/mooring)
- Acoustic trigger
- Mechanical release system
- Corrodible link
- Grapple
- Diver retrieval
- Timed release system

[3] Note, that Chains, shackles etc. can generate noise - especially if there is metal on metal contact.

6.3 Radio-linked hydrophones (RLH)

These systems are self-contained in terms of their power supply and are designed to be moored with a surface expression to allow for data transfer via radio-link. This link limits the data bandwidth and also the transmission range, but it allows real-time or near real-time data acquisition and analysis (Sousa-Lima et al. 2013a, b).

Future developments:

- Low power electronics
- Increase in data storage (ARs) and data transmission (RLHs) capacity
- Reduction in power consumption
- Reduction in size
- Reduction in self-noise
- Increase in data pre-processing speed and automation
- Information network and Integration

6.4 Fixed cable hydrophones (FCH)

The systems usually have no surface expression, are powered externally (from land or a facility at sea) and allow near real-time to real-time data acquisition and analysis. Examples:

- SOSUS (US Navy)
- Test ranges (US Navy): Autec (Bahamas), SCORE/SOAR (California), PMRF (Hawaii)
- Ocean Observatories Initiative (OOI) http://www.oceanleadership.org
- The OOI will construct a networked infrastructure of science-driven sensor systems to measure the physical, chemical, geological and biological variables in the ocean and seafloor.
- Station resent + planned stations in America: Papa (Bering Sea, 50*N, 145*W), Regional scale nodes endurance array (Westcoast Canada + US, 46N, 127W), Pioneer array (North-East coast US, 40N, 70W), Irminger Sea (Greenland, 60N, 39W), Argentinian Basin (42S, 42W), Southern Ocean (55S, 90W).
- Regional Ocean Observatories: Project Neptune (see: Regional scale nodes endurance array (Westcoast Canada +US, 46N, 127W), http://www.ooi.washington.edu/ or http://www.oceanleadership.org
- Monterey Accelerated Research System (MARS): Testbed System in Monterey Bay, CA
- ESONET (EU) Ocean Observatories in the Mediterranean Sea
- ANTARES-AMADEUS Observatory

Even though these systems provide good examples for efficient long-term monitoring systems, the drawback is that most of these systems are not publically available (i.e. either developed/used by military or as research product solely used by a particular institution or agency). However, this situation has recently changed as new systems became available (e.g. André et al. 2011):

Comparison of all types (Sousa-Lima et al. 2013a, b)

Type	Time-scale	Spatial-scale	Spectral range	Initial cost/ unit	Data	Flexible	Maintenance (no damage/damage)
AR	Hour – year	No. of units	Varies	Low	Archival	Yes	Low/ medium
RLH	Day – year	No. of units	Varies	Medium – high	Real-time or near	Yes	Medium/ high
FCH	>day - >year	Large	Potentially broad	High	Real-time or near	No	Very low/ Very high

6.5 List of (some) PAM systems available

The nature of any report on technical systems like the PAM devices implies that with the fast advancement of technical and market developments new versions of existing systems become available, often with enhanced sensor capabilities or storage capacities or even completely new products becoming available. Therefore the list of PAM systems (table 1 and 2) must be considered incomplete and outdated already on its day of publication. There are also systems existing which would not be broadly applicable for monitoring underwater sound or for detecting the presence of marine fauna, but were designed for a much more specific purpose (telemetry tags, towed systems; sometimes these systems are custom-made for a single specific research study) and can only be accessed through direct research cooperation with the manufacturer/researcher. Those systems are intentionally not listed here. Another criterion for listing was the accessibility of information – at least about the manufacturer and some basic information on the system itself – from the internet. Even though some systems have been tested and used in number of research projects (see column: 'References'), many specifications have not been tested or confirmed yet independently and no guarantee is given that the technical specifications given by the manufacturer (recording time, noise floor etc.) are correct. Also, there are no prices stated in this overview for any of the systems as those might change over time as well as depending on the specifications required for a particular research/monitoring set-up, discounts when purchasing larger number of devices etc. For all systems listed a contact (address and URL) is provided (table 2) to facilitate getting in touch with the manufacturer to inquire about more technical details and prices.

Table 1: Technical overview of PAM systems (NA = not applicable/no online information available); Alphabetic listing – sequence does not reflect any ranking.(following pages)

No.	Acronym	System name	Dimensions	Maximum deployment depth (m)	Maximum deployment time	Sampling frequency (Hz)	Frequency range(Hz)	Power supply and energy capacity	Data storage	Data format	Data resolution	Directivity pattern	Receiver sensitivity	Dynamic/ Amplitude range	Examples of species/aspects studied	Comment
	Autonomous Recorders (AR)															
1	AcousondeTM 3A (tag)	AcousondeTM 3A (tag)	3.2 cm (diameter) x 22.1 cm	3,000	14 d	22 (low-frequency channel); 232,000 (high-frequency channel)	NA	A-cell lithium battery pack	64 GB (128 GB max)	2 acoustic channels, attitude, orientation, depth, tag temperature, 3-D acceleration/ tilt, ambient light level	16 bit	NA	-201 dB dB re 1V/µPa (LP channel); -204 dB dB re 1V/µPa (HP channel); 20 dB gain selectable	up to 187 dB re 1 µPa (LP channel); 176 dB re 1 µPa (HF channel)	NA	Replaced the Compact Acoustic Probe (CAP) or Bioacoustic Probe (Bio-probe)
2	AcousondeTM 3B (tag)	AcousondeTM 3B (tag)	7.9 cm (diameter) x 22.4 cm	500	14 d	22 (low-frequency channel); 232,000 (high-frequency channel)	NA	A-cell lithium battery pack	64 GB	2 acoustic channels, attitude, orientation, depth, tag temperature, 3-D acceleration/ tilt, ambient light level	16 bit	NA	-201 dB dB re 1V/µPa (LP channel); -204 dB dB re 1V/µPa (HP channel); 20 dB gain selectable	up to 187 dB re 1 µPa (LP channel); 176 dB re 1 µPa (HF channel)	NA	

No.	Acronym	System name	Dimensions	Maximum deployment depth (m)	Maximum deployment time	Sampling frequency (Hz)	Frequency range(Hz)	Power supply and energy capacity	Data storage	Data format	Data resolution	Directivity pattern	Receiver sensitivity	Dynamic/ Amplitude range	Examples of species/aspects studied	Comment
3	AMAR G3	Autonomous Multi-Channel Acoustic Recorder Generation 3	132.1 x 40.4 cm; diamter: 16.5 cm	250 (shallow AMAR); 2,500 (deep AMAR)	Duty cycle depen-dant up to 1 yr possible	4000-128,000	10-62,720	DC power from battery pack (7 to 16 Vdc) or PoE three standard battery packs available (short, medium, and long)	Solid-state storage. 256 GB, expandable to 1.75 TB	Acoustic data as .wav formatted files; non-acoustic data as CSV files	24 bit	NA	-191 dBV/ 1 µPa (with hydro-phone 'GeoSpectrum M8'; additional gain of up to 42 dB select-able)	104 dB range (max. signal with zero gain applied is approximate-ly 170 dB re 1 µPa)	NA	Analysis software Spectro-plotter - commercially available
4	A-PANDA	Advanced Pop-up Ambient Noise Data Acquisition	30 cm (diameter) × 70 cm long	200	35 h	10,000-150,000	NA	Custom Li-Ion battery pack	40 GB hard disk	Direction of arrival estimations, time series	NA	NA	NA	NA	NA	
5	AURAL-M2	Autonomous Underwater Recorder for Acoustic Listening Model-2	With 16 batteries: 14.6 × 90 cm; with 64 batteries: 14.6 × 120 cm; with 128 batteries: 14.6 × 178 cm	300	Duty cycle depen-dant up to 1 yr depen-ding on setting parameters	256-32,768	10-16,384	Alkaline D-cell or battery pack	Compact flash 1 GB or more and 2.5" hard disk 320 GB or more	.wav, temperature and depth	16 bit	NA	NA	NA	Humpback whale, beluga, bearded seal; baleen whales	Adjustable amplifier: 16, 18, 20 and 22 dB

No.	Acronym	System name	Dimensions	Maximum deployment depth (m)	Maximum deployment time	Sampling frequency (Hz)	Frequency range(Hz)	Power supply and energy capacity	Data storage	Data format	Data resolution	Directivity pattern	Receiver sensitivity	Dynamic/ Amplitude range	Examples of species/aspects studied	Comment
6	C-POD	C-POD	660 mm length × 90 mm diameter; 2.1 kg without batteries, 3.55 kg with batteries	At least 100 m	4 mo	5Mz	20,000-160,000	Alkaline battery pack	Two removable 4 GB SD-cards	Dominant frequency of the first 10 cycles, the final zero-crossing interval, a bandwidth index, envelope slope, angle of the POD to the vertical, and temperature	8 bit	Horizontal: Omnidirectional	NA	NA	All odontocete species except sperm whale (*P. macro-cephalus*)	Analysis software CPOD.exe is provided
7	digitalHyd SR-1	digitalHyd SR-1	50 mm diameter x 323 mm length	100	Duty cycle dependant 12 hours continu-ous recording (expandable with larger battery packs)	52,734 or 105,469 (selectable)	1 - 25,800 or 1 - 51,600	3.7 VDC, 3400 mAh Lithium-Ion battery (expandable with larger battery packs)	up to 128GB	.wav	16 or 24 bit	NA	-162.2 to -126.1 dB re 1V/μPa	46.3 dB - 172.5 dB re 1 μPa	NA	

No.	Acronym	System name	Dimensions	Maximum deployment depth (m)	Maximum deployment time	Sampling frequency (Hz)	Frequency range(Hz)	Power supply and energy capacity	Data storage	Data format	Data resolution	Directivity pattern	Receiver sensitivity	Dynamic/ Amplitude range	Examples of species/aspects studied	Comment
8	DASAR	Directional Autonomous Seafloor Acoustic Recorders	Cylinder of 30 by 36 cm	30	45 d	2,400	NA	Alkaline battery pack	30 GB disk drive	3 channels provide azimuthal bearings to sound sources	NA	NA	NA	NA	*Balaena mysticetus*	
9	Deep C-POD	C-POD	680 mm length × 100 mm diameter	At least 2,000 m	4 mo	20,000-160,000	20,000-160,000	Alkaline battery pack	Two removable 4 GB SD-cards	Dominant frequency of the first 10 cycles, the final zero-crossing interval, a bandwidth index, envelope slope, angle of the POD to the vertical, and temperature	8 bit	Horizontal: Omnidirectional	NA	NA	All odontocete species except sperm whale (*P. macrocephalus*)	Analysis software CPOD.exe is provided

No.	Acronym	System name	Dimensions	Maximum deployment depth (m)	Maximum deployment time	Sampling frequency (Hz)	Frequency range(Hz)	Power supply and energy capacity	Data storage	Data format	Data resolution	Directivity pattern	Receiver sensitivity	Dynamic/ Amplitude range	Examples of species/aspects studied	Comment
10	DMON	Digital Acoustic Monitor	70 mm (diameter) × 210 mm	1,500	LF 50 d; MF 180 h	Examples of three possible frequency settings: LF 80,000; MF 240,000; HF 480,000	10 - 150,000	Rechargeable Li-Ion battery	32 GB flash memory (as of 2008; by now likely much larger memory available)	Sound files (3 independent acoustic channels), temperature, depth, and orientation	NA	NA	NA	NA	Fish; baleen whales, beaked whales	can be combined with external GPS and radio telemetry as part of a marine mammal monitoring installation; On-board digital signal processor
11	DSG-Ocean	Ocean Digital Spectrogram Recorder	11.4 cm diameter × 63.5 cm	100 m for PVC housing and 2,000 m for aluminum hous-ing	Calculated by proprietary software during set-up based on memory size and recording schedule	80,000; burst recordings of up to 400,000	NA	Alkaline battery pack; 8 x 3-D-cell battery holders	Two 32 GB SDHC cards or one 128 GB SDHC card	WAV files; FAT32 file system that stores latitude, longitude, depth, calibrations, and time stamps	NA	NA	NA	NA	Invertebrates, fishes, and marine mammals	MATLAB scripts for opening DSG files directly as well as open source MATLAB code for 3D motion processing is provided

No.	Acronym	System name	Dimensions	Maximum deployment depth (m)	Maximum deployment time	Sampling frequency (Hz)	Frequency range(Hz)	Power supply and energy capacity	Data storage	Data format	Data resolution	Directivity pattern	Receiver sensitivity	Dynamic/ Amplitude range	Examples of species/aspects studied	Comment
12	EAR	Ecological Acoustic Recorder	For shallow water deployment (<46 m): 10.16 cm diameter by 60 cm long cylinder; for deep water (up to 500 m): additional float collar	500	Duty cycle dependant up to >1 y	up to 64,000	1 - 28,000	Alkaline battery pack	120 Gbyte 2.5 in. Toshiba hard disk drive (flash memory card periodically transferred to a hard drive) (as of 2008)	Binary files	16 bit	NA	NA	NA	*Stenella longirostris*	
13	EA-SDA14	EA-SDA14	12 cm x 32 cm; 12 cm x 55 cm; 12 cm x 1210 cm;	700	Duty-cycle depen-dent; can be >1 yr; up to 45 days cont. recording at 96 kHz sampling rate;	3 - 1,000,000	selectable, depending on hydro-phone	6 Li-SOCl2 batteries; Additional battery (up to 54) available	128GB SD Card; 1TB/2TB HDD or 600GB SSD memory extension available	. .wav	24 bit	Selectable; depen-ding on hydro-phone	-4 to +16 dB gain available	>100 dB dyn. range	NA	4 channels;

No.	Acronym	System name	Dimensions	Maximum deployment depth (m)	Maximum deployment time	Sampling frequency (Hz)	Frequency range(Hz)	Power supply and energy capacity	Data storage	Data format	Data resolution	Directivity pattern	Receiver sensitivity	Dynamic/ Amplitude range	Examples of species/aspects studied	Comment
14	EA-SDA14-1000	EA-SDA14-1000	12 cm x 55 cm	700	Duty-cycle depend-ent can be >1 yr; up to 45 days cont. recording at 96 kHz sampling rate;	3 - >500,000	selectable, depending on hydro-phone	18 D-cells	128GB SD Card; 1TB/2TB HDD or 600GB SSD memory extension available	.wav	24 bit	Selectable; depending on hydrophone	-4 to +16 dB gain available	>100 dB dyn. range	NA	4 channels;
15	icListen LF	icListen LF	4.5 cm (diameter) X 20 cm	200 or 3500	NA	up to 16,000	0.1 - 6,400	12 – 48 VDC	32 GB, FAT32	.wav	24 bit	NA	NA	NA	NA	PC software 'Lucy' available
16	microMARS	microMARS MM300-2 / MM300-8	63 mm (diameter) x 195 mm length	300 (avail. Up to 6000 m)	46 days at max. sampling rate of 250 kHz (460 days at 25 kHz)	up to 250,000		512 GB (type: MM300-2) or 2TB (MM300-8)								standard hyrdophone up to 40 kHz frequency response
17	MT 150US	MT 150US	9 cm (diameter) x 30 cm	NA	NA	Up to 96,000	up to 48,000	12,000 mA NiMH battery pack; fast rechargeable	64 GB compact flash card	.wav or .mp3 files	24 bit	NA	NA	NA	Whales and dolphins	
18	MT 200	MT 200	9 cm (diameter) x 50 cm	NA	NA	Up to 96,000	up to 48,000	26,000 mA NiMH battery pack; fast rechargeable	64 GB compact flash card	.wav or .mp3 files	24 bit	NA	NA	NA	Whales and dolphins	

No.	Acronym	System name	Dimensions	Maximum deployment depth (m)	Maximum deployment time	Sampling frequency (Hz)	Frequency range(Hz)	Power supply and energy capacity	Data storage	Data format	Data resolution	Directivity pattern	Receiver sensitivity	Dynamic/ Amplitude range	Examples of species/aspects studied	Comment
19	OCEANPOD	NA	11 cm (diameter) x 45 cm	70 m for PVC (1,000 m for aluminium)	23 d	48,000 or 96,000	NA	Alkaline D-cells	32 GB	PCM, .mp3	24-bit	NA	NA	NA	Cetaceans, fish, sea state, and vessels	
20	PANDA	Pop-up Ambient Noise Data Acquisition	30 kg without anchor	200	9-10 d	10-10,000	NA	Recharge-able lithium video camera batteries	12 GB hard drive	Time series	NA	NA	NA	NA	NA	
21	Pop-up or MARU*	Marine Acoustic Recording Unit	Single sphere: 48.3 cm high and 58.4 cm diameter Double-bubble: 100 cm high and 58.4 cm diameter	2,500 (acoustic release depen-dent); Up to 6,000 (on moorings)	90 d	2,000-64,000	NA	Alkaline battery pack (Double-bubble configuration doubles power capacity.)	120 GB hard drive	Binary restored to sound files (aiff)	NA	NA	NA	NA	*B. musculus, B. physalus, B. bonarensis, M. novaeangliae, Eubalaena glacialis*	Software: Raven; Xbat
22	RASP 12- C24	Registratore Acustico Subacqueo Programm-abile	9 cm (diameter) x 50 cm	500	184 h	Up to 96,000	up to 48,000	Battery pack NiMH fast rechargeable	8 GB compact flash card	.wav or .mp3 files	24 bit	NA	NA	NA	Whales and dolphins	

No.	Acronym	System name	Dimensions	Maximum deployment depth (m)	Maximum deployment time	Sampling frequency (Hz)	Frequency range(Hz)	Power supply and energy capacity	Data storage	Data format	Data resolution	Directivity pattern	Receiver sensitivity	Dynamic/ Amplitude range	Examples of species/aspects studied	Comment
23	RUDAR™	Remote Underwater Digital Acoustic Recorder	17.8 cm, 36.4 kg or 45.5 kg with batteries	1,500 or 3,500	Duty cycle dependant	Selectable sampling rates up to 192,000	NA	Rechargeable Li-Ion batteries	Compact flash cards for short deploy-ments and hard disks for longer deployment	Up to 4 hydrophone channels, .wav	NA	NA	NA	NA	Cetaceans	
24	Runes	Remote Underwater Noise Evaluation System	50 cm height x 107 cm diameter	500	Duty cycle depen-dant 30 days cont. recording with lead acid batteries, greater with lithium batteries	500,000	20-170,000	Lead acid batteries or lithium batteries	256GB SSD	NA	16 bit	Horizontal – Omni-directional; Vertical - Cardioid	NA	50 dB - 180 dB re 1 µPa	NA	System can be rented
25	Song Meter SM2M+	Song Meter Autonomous Submersible Recorder	16.5 cm diameter × 79.4 cm long	150	Up to 2 months on 48 kHz sampling rate or 13 d at 384 kHz sampling rate	up to 384,000	2 - 192,000	alkaline D cell or lithium manganese batteries	128 GB with SDHC or 512 GB with SDXC	RMS level, SPL receive levels	16 bit	NA	NA	NA	NA	Song Scope analysis software available

No.	Acronym	System name	Dimensions	Maximum deployment depth (m)	Maximum deployment time	Sampling frequency (Hz)	Frequency range(Hz)	Power supply and energy capacity	Data storage	Data format	Data resolution	Directivity pattern	Receiver sensitivity	Dynamic/ Amplitude range	Examples of species/aspects studied	Comment
26	SongMeter SM2M+ DeepWater	Song Meter Autonomous Submersible Recorder - Deep Water	16.5 cm diameter × 148 cm long	1500	Duty cycle dependent; ultrasonic sample rates: 50 d recording with D-cell, 84 d with LiMN batteries	up to 384,000	2 - 192,000	64 alkaline D cell batteries or lithium manganese	maximum of 512 GB on 4 SDHC or SDXC cards	RMS level, SPL receive levels	16 bit	NA	NA	NA	NA	2 channels; Song Scope analysis software available
27	Sono.Vault	Sono.Vault	180 mm diameter x 1550 mm length (without mooring frame)	3500	Duty cycle dependent up to two years	up to 192 kHz	3-100,000	Up to 4500Wh (78 Lithium D-cells)	7x SDHC / storage module; 1.1 TB (max. of 4.4 TB possible)	.wav	16 or 24 bit; 16 bit up to 220ksps	Spherical	-193 dB re 1V/µPa	NA	NA	6-48 dB gain; hydrophone: TC4037-3
28	SoundTrap 202	SoundTrap 202	200 mm L x 60 mm D	500	Duty cycle dependent 14 days on cont. at 96 kHz samling rate,	48, 96, 144 and 288 kHz	20-60,000 (150 kHz version available on request)			.wav	16 bit SAR	omnidirectional at 60 kHz		max. level before clipping: 186 dB re 1 µPa; Selfnoise: below ss-0 up to 2 kHz, <32 dB up to 60 kHz	NS	Self-calibration check; Firmware is available under GPL open source license for real time processing

No.	Acronym	System name	Dimensions	Maximum deployment depth (m)	Maximum deployment time	Sampling frequency (Hz)	Frequency range(Hz)	Power supply and energy capacity	Data storage	Data format	Data resolution	Directivity pattern	Receiver sensitivity	Dynamic/ Amplitude range	Examples of species/aspects studied	Comment
29	SYLence	SYLence	12 cm x 55 cm	100		48KHz, 96KHz and 192KHz	up to 80,000	18 D-cells	128 or 256 GB on SD card; hard-drive storage	.wav	16 or 24 bits	NA	NA	NA	NA	2 channels; Song Scope analysis software available
	Systems linked to land-based station (RLH/ FCH)															
30	BA-SDA14	BA-SDA14	Float dimensions : 60 cm (diameter); Tube: 15 cm x 157 cm		12 d cont. recording	3 - >900,000	NA	1000W.H rechargeable battery pack	128GB SD Card up to 2TB hard-drive	.wav; embedded DSP	24 bit	NA	NA	>100 dB dyn. range	NA	4 hydrophone inputs; GPS antenna; additonal sensor can be attached
31	LIDO	Project: Listening to the Deep Ocean environment	NA	nearshore /offshore	Continuous	NA	1 - 200,000	platform specific	platform/ link-specific	raw data or processed data	NA	NA	NA	NA	Cetaceans (mainly toothed whales)	Real-time detection and classification of cetacean clicks/ SONS-DCL real-time analysis software available
32	icListen LF	icListen LF	4.5 cm (diameter) X 20 cm	200 or 3500	NA	up to 16,000	0.1 - 6,400	12 – 48 VDC	32 GB, FAT32	.wav	24 bit	NA	NA	NA		PC software 'Lucy' available; High frequency version (icListen HF) available, but no information found online

No.	Acronym	System name	Dimensions	Maximum deployment depth (m)	Maximum deployment time	Sampling frequency (Hz)	Frequency range(Hz)	Power supply and energy capacity	Data storage	Data format	Data resolution	Directivity pattern	Receiver sensitivity	Dynamic/ Amplitude range	Examples of species/aspects studied	Comment
33	PAMBuoy	PAMBuoy ® marine mammal monitoring	various platforms available (moored buoys: up to 3 m x 3 m x 7.2 m, waveglider: 0.7 m length)	in waters up to 5,000 m deep for largest buoy	continuous	500000 (typical, 1 MHz maximum)	2 - 200,000	solar panels	onboard: 32 Gb SD onshore: customer defined; through online-detection data reduction to <1% can be achieved	NA	NA	horizontal: omni-directional	-186 or 180 dB re 1V/μPa	NA	aiming at: baleen whales, beaked & sperm whales, dolphins and porpoises	4 channels; up to 30 dB gain per channel available; Detection/data analysis software PAMGUARD freely available
34	OCEANBASE	NA	9 cm (diameter) x 45 cm	70 m for PVC (1,000 m for aluminium)	Until storage capacity is reached	Until 100 kHz according to user's application or 44, 96, 192 kHz	NA	Depending on user's application	SSD 128 GB expandable to 1 TB or more	PCM, .mp3; non-acoustic signals in CSV format	12 or 16-bit	NA	NA	NA	Cetaceans, sea state, and vessels	

Table 2. Manufacturer Information

Number (in Table 1 and 2)	Manufacturer name	Address	URL	Last viewed
1	Greeneridge Sciences, Inc.	Cetacean Research Technology, 4728 12th Ave. NE - Seattle, WA 98105 USA	http://www.cetaceanresearch.com/hydrophone-systems/underwater-recording/acousonde/index.html	Jan-14
2	Greeneridge Sciences, Inc.	Cetacean Research Technology, 4728 12th Ave. NE - Seattle, WA 98105 USA	http://www.cetaceanresearch.com/hydrophone-systems/underwater-recording/acousonde/index.html	Jan-14
3	JASCO Research Ltd, Canada	http://www.jasco.com/ContactUs.html	http://www.jasco.com/Default.html	Jan-14
4	ARL of Tropical Marine Science Institute in National University of Singapore	Acoustic Research laboratory, Tropical Marine Science Institute, National University of Singapore, 12A Kent Ridge Road, Singapore 119222	http://arl.nus.edu.sg/twiki/bin/view/ARL/PANDA	Jan-14
5	Multi-Electronique Inc., France (MTE)	Multi-Electronique (MTE) Inc., 1, 8 e Avenue, Rimouski Québec G5L 2L9, Canada	http://multi-electronique.com/pages/auralm2en.htm	Jan-14
6	Chelonia Limited, UK	Chelonia Limited, The Barkhouse, North Cliff, Mousehole, Cornwall TR19 6PH, UK	http://www.chelonia.co.uk/	Jan-14
7	MarSensing	MARSENSING LDA, Centro Empresarial Pav. A5, Campus de Gambelas, 8005-139 Faro, Portugal	www.marsensing.com	Jan-14

Number (in Table 1 and 2)	Manufacturer name	Address	URL	Last viewed
8	Greeneridge Sciences, Inc. incorporated DIFAR sensors from Sparton Electronics, FL, into DASARs.	Greeeridge Sciences, 6160-C Wallace Becknell Road, Santa Barbara, CA 93117, USA	http://www.greeneridge.com/technology.html	Feb-14
9	Chelonia Limited, UK	Chelonia Limited, The Barkhouse, North Cliff, Mousehole, Cornwall TR19 6PH, UK	http://www.chelonia.co.uk/	Jan-14
10	Woods Hole Oceanographic Institution (WHOI)	School of Biology, Biomedical Sciences Research Complex, University of St Andrews, St Andrews, Fife, KY16 9ST, UK	ftp://soest.hawaii.edu/eroth/outgoing/forJim/DMONflyerV1.2.pdf	Jan-14
11	Loggerhead Instruments	Loggerhead Instruments, 6576 Palmer Park Circle, Sarasota, FL 34238, USA	http://loggerheadinstruments.com/	Jan-14
12	Marc O. Lammers, Oceanwide Science Institute (OSI), and Kevin Wong, NOAA Fisheries, Pacific Islands Fisheries Science Center, Coral Reef Ecosystem Division (CRED), Hawaii	Oceanwide Science Institute, P.O. Box 61692 Honolulu, HI 96839, USA	http://oceanwidescience.org/docs/EAR.htm	Jan-14
13	Rtsys	Rtsys, 25 rue Michel Marion, 56850 Caudan, France	http://www.rtsys.eu/en/underwater-acoustics	Feb-14
14	Rtsys	Rtsys, 25 rue Michel Marion, 56850 Caudan, France	http://www.rtsys.eu/en/underwater-acoustics	Feb-14

Number (in Table 1 and 2)	Manufacturer name	Address	URL	Last viewed
15	Instrument Concepts Inc.	Instruments Concepts Inc., Hill House, 11 Lornevale Road, Great Village, Nova Scotia, B0M 1L0, Canada	http://instrumentconcepts.com/Contact/tabid/66/Default.aspx	Feb-14
16	Desert Star Systems LLC	Desert Star Systems LLC, 3261 Imjin Road, Marina, CA 93933 USA	http://www.desertstar.com/acoustic-recorders.html	Jan-14
17	Nauta Ricerca e Consulenza Scientifica, Italia	NAUTA-r.c.s., Strada della Carità 8, 20135 Milano. Italy	http://www.nauta-rcs.it/english/page117/page25/page26/	Jan-14
18	Nauta Ricerca e Consulenza Scientifica, Italia	NAUTA-r.c.s., Strada della Carità 8, 20135 Milano. Italy	http://www.nauta-rcs.it/english/page117/page25/page26/	Jan-14
19	LADIN (Laboratório de Dinâmica e Instrumentação), Universidade de São Paulo, São Paulo, Brazil	Laboratório de Dinâmica e Instrumentação, Departamento de Engenharia Mecânica – EPUSP, Av. Prof. Mello de Moraes, 2231, CEP 05508-970 Cidade universitaria - Universidade de São Paulo, Brazil	http://www.ladin.usp.br/OPODE.html	Jan-14
20	Acoustic Research Laboratory (ARL) of Tropical Marine Science Institute in National University of Singapore	Acoustic Research laboratory, Tropical Marine Science Institute, National University of Singapore, 12A Kent Ridge Road, Singapore 119222	http://arl.nus.edu.sg/twiki/bin/view/ARL/PANDA	Jan-14
21	Bioacoustics Research Program (BRP) at the Lab of Ornithology (CLO), Cornell University	Bioacoustics Research Program, Cornell Lab of Ornithology, 159 Sapsucker Woods Road, Ithaca, NY 14850, USA	http://www.birds.cornell.edu/brp/hardware/pop-ups	Jan-14

Number (in Table 1 and 2)	Manufacturer name	Address	URL	Last viewed
22	Nauta Ricerca e Consulenza Scientifica, Italia	NAUTA-r.c.s., Strada della Carità 8, 20135 Milano. Italy	http://www.nauta-rcs.it/english/page117/page25/page26/page1/	Jan-14
23	Cetacean Research Technology	Cetacean Research Technology, 4728 12th Ave. NE - Seattle, WA 98105, USA	http://www.cetaceanresearch.com/hydrophone-systems/rudar/index.html#rudar	Jan-14
24	Kongsberg Maritime Ltd.	Kongsberg Maritime Ltd., Campus 1, Aberdeen Innovation Park, Balgownie Road, Bridge of Don, Aberdeen AB22 8GT, UK	http://www.km.kongsberg.com/ks/web/nokbg0240.nsf/AllWeb/7135044E01BE8932C1257142004C679E?OpenDocument	Jan-14
25	Wildlife Acoustics, Inc., USA	Wildlife Acoustics, Inc., 3 Clock Tower Place, Maynard, MA 01754-2549, USA	http://www.wildlifeacoustics.com/products/song-meter-sm2-plus-submersible/specifications	Jan-14
26	Wildlife Acoustics, Inc., USA	Wildlife Acoustics, Inc., 3 Clock Tower Place, Maynard, MA 01754-2549, USA	http://www.wildlifeacoustics.com/products/song-meter-sm2-plus-deep-water/specifications	Feb-14
27	Subsea Systems GmbH, Germany	develogic GmbH, Eiffestr. 598, 20537 Hamburg, Germany	http://www.develogic.de/products/ss-r/sonovault/	Feb-14
28	Ocean Instruments New Zealand	Ocean Instruments New Zealand, 961 Sandspit Rd, Warkworth, Auckland, New Zealand	http://www.oceaninstruments.co.nz/soundtrap-202/	Feb-14
29	Rtsys	Rtsys, 25 rue Michel Marion, 56850 Caudan, France	http://www.rtsys.eu/en/underwater-acoustics	Feb-14
30	Rtsys	Rtsys, 25 rue Michel Marion, 56850 Caudan, France	http://www.rtsys.eu/en/underwater-acoustics	Feb-14

Number (in Table 1 and 2)	Manufacturer name	Address	URL	Last viewed
31	Laboratori d'Aplicacions Bioacústiques	Laboratori d'Aplicacions Bioacústiques, Centre Tecnològic de Vilanova i la Geltrú, Universitat Politècnica de Catalunya, Avda. Rambla Exposició s/n, 08800 Vilanova i la Geltrú, Spain	http://listentothedeep.com/acoustics/index.html	Feb-14
32	Instrument Concepts Inc.	Instruments Concepts Inc., Hill House, 11 Lornevale Road, Great Village, Nova Scotia, B0M 1L0, Canada	http://instrumentconcepts.com/Contact/tabid/66/Default.aspx	Feb-14
33	SMRU Limited	PAMBuoy®, Unit 6, New Technology Centre, North Haugh, St. Andrews, Fife KY16 9SR, U.K.	http://www.pambuoy.com	Feb-14
34	LADIN, Universidade de São Paulo, São Paulo, Brazil	Laboratório de Dinâmica e Instrumentação, Departamento de Engenharia Mecânica – EPUSP, Av. Prof. Mello de Moraes, 2231, CEP 05508-970 Cidade universitaria - Universidade de São Paulo, Brazil	http://www.ladin.usp.br/OBASE.html	Feb-14

7 Conclusions

There are still numerous hurdles to be overcome before acoustic methods can be reliably used to estimate abundance, which is the ultimate goal for both ecosystem studies and management purposes. It is clear, however, that passive acoustic monitoring systems provide a very efficient monitoring method which can complement or even be used as alternative to visual survey methods. Passive acoustic monitoring systems vary widely in cost, need of maintenance, data availability, deployment longevity, flexibility and surface expression. Consequently, there is no right answer to which system should be ideally used, but rather the biology of the species of interest has to be considered. Other relevant aspects like the total costs of the systems (incl. deployment and maintenance), the bathymetry and oceanographic conditions of the deployment area have to be taken into account as well. The definition of the system specifications and configuration has ultimately to be based on clearly defined (research) questions.

8 Quality Assurance

IMARES utilises an ISO 9001:2008 certified quality management system (certificate number: 124296-2012-AQ-NLD-RvA). This certificate is valid until 15 December 2015. The organisation has been certified since 27 February 2001. The certification was issued by DNV Certification B.V. Furthermore, the chemical laboratory of the Fish Division has NEN-EN-ISO/IEC 17025:2005 accreditation for test laboratories with number L097. This accreditation is valid until 1th of April 2017 and was first issued on 27 March 1997. Accreditation was granted by the Council for Accreditation.

9 References

André, M., van der Schaar, M., Zaugg, S., Sánchez, A.M., and Castell, J.V. (2011). Listening to the Deep: Live monitoring of cetacean noise and cetacean acoustic signals. Marine Pollution Bulletin 63: 18-26.

Au, W.W.L., Moore, P.W.B., and Pawloski, D. (1986). Echolocation transmitting beam of the Atlantic bottlenose dolphin. Journal of the Acoustical Society of America 80: 688–691.

Au, W.W.L. (1993). The Sonar of Dolphins. Springer Verlag.

Barlow, J., and Taylor, B.L. (2005). Estimates of sperm whale abundance in the northeastern temperate Pacific from a combined acoustic and visual survey. Marine Mammal Science 21: 429–445.

Barnes, C.R., Best, M.M.R., Bornhold, B.D., Juniper, S.K., Pirenne, B., and Phibbs, P. (2007). The NEPTUNE Project—a cabled ocean observatory in the NE Pacific: Overview, challenges and scientific objectives for the installation and operation of Stage I in Canadian waters. Pp. 308–313 in Symposium on Underwater Technology and Workshop on Scientific Use of Submarine Cables and Related Technologies, Tokyo, Japan. IEEE Press, Piscataway, NJ. doi:10.1109/UT.2007.370809.

Buckland, S.T., Anderson, D.R., Burnham, K.P., Laake, J.L., Borchers, D.L., and Thomas, L. (2001). *Introduction to Distance Sampling: Estimating Abundance of Biological Populations*. Oxford University, Oxford.

Burgess, W.C., Tyack, P.L., Le Boeuf, B.J., and Costa, D.P. (1998). A programmable acoustic recording tag and first results from free-ranging northern elephant seals. Deep-Sea Research Part II 45: 1327-1351. http://dx.doi.org/10.1016/S0967-0645(98)00032-0

Burtenshaw, J.C., Oleson, E.M., Hildebrand, J.A., McDonald, M.A., Andrew, R.K., Howe, B.M., and Mercer, J.A. (2004). Acoustic and satellite remote sensing of blue whale seasonality and habitat in the northeast Pacific. Deep Sea Research Part II 51: 967–986.

Caldwell, M.C., and Caldwell, D.K. (1965). Individualized whistle contours in bottlenosed dolphins (*Tursiops truncatus*). Nature, 207, 434–435.

Caldwell, M.C., Caldwell, D.K., and Tyack, P.L. (1990). Review of the signature-whistle hypothesis for the Atlantic Bottlenose Dolphin. In: S. Leatherwood and R.R. Reeves (eds.): *The Bottlenose Dolphin*, pp. 199–234. New York: Academic Press.

Calupca, T. A., Fristrup, K. M., and Clark, C. W. (2000). A compact digital recording system for autonomous bioacoustic monitoring. The Journal of the Acoustical Society of America, 108: 2582. http://dx.doi.org/10. 1121/ 1.4743595

Cato, D. (1991). Songs of humpback whales: The Australian perspective. Memoirs of the Queensland Museum 30: 277–290.

Cato, D.H. (1998). Simple methods of estimating source levels and locations of marine animal sounds. Journal of the Acoustical Society of America 104: 1667–1678.

Clark, C.W. (1995). Application of U.S. Navy underwater hydrophone arrays for scientific research on whales. Scientific Report, International Whaling Commission 44: 210–213.

Clark, C. W., Charif, R., Mitchell, S., and Colby, J. (1996). Distribution and behavior of the bowhead whale, *Balaena mysticetus*, based on analysis of acoustic data collected during the 1993 spring migration off Point Barrow, Alaska. Reports of the International Whaling Commission, 46: 541-552.

Clark, C.W., D. Gillespie, D.P. Nowacek, and S.E. Parks (2007). Listening to their world: Acoustics for monitoring and protecting right whales in an urbanized world. In: S.D. Kraus and R.M. Rolland (eds.): *The Urban Whale*, pp. 333–357, Harvard University Press, Cambridge, MA.

Clausen, K.T., Wahlberg, M., Beedholm, K., DeRuiter, S., and Madsen, P.T. (2010). Click communication in harbour porpoises (*Phocoena phocoena*). Bioacoustics 20: 1-28.

Cummings, W.C., Brahy, B.D., and Herrnkind, W.F. (1964). The occurrence of underwater sounds of biological origin off the west coast of Bimini, Bahamas. In: W.N. Tavolga (ed): *Marine Bio-acoustics*, pp. 27–43, Pergamon, NY.

Cummings, W.C., and Thompson, P.O. (1971). Underwater sounds from the blue whale, *Balaenoptera musculus*. Journal of the Acoustical Society of America 50: 1193–1198.

Dudzinski, M.K., Thomas, J.A., and Gregg, J.D. (2009). Communication in marine mammals. In: W.F. Perrin, B. Würsig and J.G.M. Thewissen (eds.): *Encyclopedia of marine mammals*, pp.260-269, Academic Press, Burlington, MA.

Dudzinksi, K., Brown, S.J., Lammers, M., Lucke, K., Mann, D., Simard, P., Wall, C., Rasmussen, M., Magnúsdóttir, E. E., Tougaard, J. and Eriksen, N. (2011). Trouble-shooting deployment and recovery options for various stationary passive acoustic monitoring devices in both shallow and deep water applications. Journal of the Acoustical Society of America 129(1): 436-448.

Fletcher, S., Le Boeuf, B.J., Costa, D.P., Tyack, P.L., and Blackwell, S.B. (1996). Onboard acoustic recording from diving northern elephant seals. Journal of the Acoustical Society of America 100: 2531-2539. http://dx.doi.org/10.1121/1.417361

Fox, C. G., Matsumoto, H., and Lau, T. A. (2001). Monitoring Pacific Ocean seismicity from an autonomous hydrophone array. Journal of Geophysical Research 106(B3): 4183-4206. http://dx.doi.org/10.1029/2000JB900404

François, R.E., and Garrison, G.R. (1982). Sound absorption based on ocean measurements: Part II: Boric acid contribution and equation for total absorption. Journal of the Acoustical Society of America 72: 1879–1890.

Janik, V.M. (2000). Source levels and the estimated active space of bottlenose dolphin (*Tursiops truncatus*) whistles in the Moray Firth, Scotland. Journal of Comparative Physiology A 186: 673–680.

Johnson, D.H., and Dudgeon, D.E. (1993). Array Signal Processing: Concepts and Techniques. Prentice-Hall, Englewood Cliffs, NJ.

Johnson, M. P., and Tyack, P. L. (2003). A digital acoustic recording tag for measuring the response of wild marine mammals to sound. IEEE Journal of Oceanic Engineering, 28(1): 3-12. http://dx.doi.org/10.1109/JOE. 2002.808212

Kyhn, L. A., Tougaard, J., Amundin, M., Stenback, J., Teilmann, J., and Wennerberg, W. (2008). Validating passive acoustic monitoring data loggers by visual observations. Journal of the Acoustical Society of America 123: 3208. http://dx.doi.org/10.1121/1.2933380

Madsen, P. T., Wahlberg, M., and Møhl B. (2002a). Male sperm whale (*Physeter macrocephalus*) acoustics in a high-latitude habitat: implications for echolocation and communication. Behavioural Ecology and Sociobiology 53: 31–41.

Madsen, P.T., Payne, R., Kristiansen, N.U., Kerr, I., and Møhl, B. (2002b). Sperm whale sound production studied with ultrasound-time-depth-recording tags. Journal of Experimental Biology 205: 1899–1906.

McDonald, M.A., Calambokidis, J., Teranishi, A.M., and Hildebrand, J.A. (2001). The acoustic calls of blue whales off California with gender data. Journal of the Acoustical Society of America 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. Journal of Cetacean Research and Management 4: 261–266.

McDonald, M.A., and Fox, C.G. (1999). Passive acoustic methods applied to fin whale population density estimation. Journal of the Acoustical Society of America 105: 2643–2651.

Mellinger, D. K., Stafford, K. M., and Fox, C. G. (2004a). Seasonal occurrence of sperm whale (*Physeter macrocephalus*) sounds in the Gulf of Alaska, 1999-2001. Marine Mammal Science 20: 48-62. http://dx.doi.org/10.1111/j.1748-7692.2004.tb01140.x

Mellinger, D. K., Stafford, K. M., Moore, S. E., Munger, L., and Fox, C. G. (2004b). Detection of North Pacific right whale (*Eubalaena japonica*) calls in the Gulf of Alaska. Marine Mammal Science 20: 872-879. http://dx.doi.org/10.1111/j.1748-7692.2004.tb01198.x

Mellinger, D.K., Stafford, K.M., Moore, S.E., Dziak, R.P., and Matsumoto, H. (2007). An overview of fixed passive acoustic observation methods for cetaceans. Oceanography 20 (4): 36–45.

Møhl, B., Wahlberg, M., Madsen, P.T., Miller, L.A., and Surlykke, A. (2000). Sperm whale clicks: Directionality and source level revisited. Journal of the Acoustical Society of America 107: 638–648.

Moore, S.E., Stafford, K.M., Mellinger, D.K., and Hildebrand, J.A. (2006). Listening for large whales in offshore waters of Alaska. BioScience 56: 49–55.

Morisaka, T., and Connor, R. C. (2007). Predation by killer whales (*Orcinus orca*) and the evolution of whistle loss and narrow-band frequency clicks in odontocetes. Journal of Evolutionary Biology 20: 1439–1458.

Munger, L. M., Mellinger, D. K., Wiggins, S., Moore, S. E., and Hildebrand, J. A. (2005). Performance of spectrogram cross-correlation in detecting right whale calls in long-term recordings from the Bering Sea. Canadian Acoustics 33(2): 25-34.

Nieukirk, S. L., Stafford, K. M., Mellinger, D. K., Dziak, R. P., and Fox, C. G. (2004). Low frequency whale and seismic airgun sounds recorded in the mid-Atlantic Ocean. The Journal of the Acoustical Society of America 115: 1832-1843. http://dx.doi.org/10.1121/1.1675816

Oswald, J.N., Rankin, S., and Barlow, J. (2004). The effect of recording and analysis bandwidth on acoustic identification of delphinid species. Journal of the Acoustical Society of America 116: 3178–3185.

Parks, S.E., and Tyack, P.L. (2005). Sound production by North Atlantic right whales (*Eubalaena glacialis*) in surface active groups. Journal of the Acoustical Society of America 117: 3297–3306.

Payne, R., and Webb, D. (1971). Orientation by means of long range acoustical signalling in baleen whales. Annals of the New York Academy of Sciences 188: 110–141.

Rankin, S., Ljungblad, D.K., Clark, C.W., and Kato, H. (2005). Vocalizations of Antarctic blue whales, *Balaenoptera musculus intermedia*, recorded during the 2001–2002 and 2002–2003 IWC-SOWER circumpolar cruises, Area V, Antarctica. Journal of Cetacean Research and Management 7: 13–20.

Richardson, W. J., Greene, C. R., Jr., Malme, C. I., and Thomson, D. H. (1995). *Marine mammals and noise*. Academic Press, San Diego, CA.

Sayigh, L.S., Tyack, P.L., Wells, R.S. and Scott, M.D. (1990). Signature whistles of free-ranging bottlenose dolphins *Tursiops truncatus*: stability and mother-offspring comparisons. Behavioural Ecology and Sociobiology 26: 247–260.

Širović, A., Hildebrand, J.A., Wiggins, S.M., McDonald, M.A., Moore, S.E., and Thiele, D. (2004). Seasonality of blue and fin whale calls and the influence of sea ice in the Western Antarctic Peninsula. Deep-Sea Research Part II 51: 2327–2344.

Širović, A., Hildebrand, J.A., and Wiggins, S.M. (2007). Blue and fin whale call source levels and propagation range in the Southern Ocean. Journal of the Acoustical Society of America 122: 1208–1215.

Sousa-Lima, R.S., Norris, T.F., Oswald, J.N., and Fernandes, D.P. (2013a). A Review and Inventory of Fixed Autonomous Recorders for Passive Acoustic Monitoring of Marine Mammals. Aquatic Mammals 39(1): 23-53. doi 10.1578/AM.39.1.2013.23

Sousa-Lima, R.S., Norris, T.F., Oswald, J.N., and Fernandes, D.P. (2013b). Errata – A Review and Inventory of Fixed Autonomous Recorders for Passive Acoustic Monitoring of Marine Mammals. Aquatic Mammals, 39(1): 23-53. doi 10.1578/AM.39.1.2013.23

Stafford, K.M., Fox, C.G., and Clark, D.S. (1998). Longrange detection and localization of blue whale calls in the northeast Pacific using military hydrophone arrays. Journal of the Acoustical Society of America 104: 3616–3625.

Stafford, K.M., Nieukirk, S.L., and Fox, C.G. (1999). Low frequency whale sounds recorded on hydrophones moored in the eastern tropical Pacific. Journal of the Acoustical Society of America 106: 3687-3698. http://dx.doi.org/10.1121/1.428220

Stafford, K.M., Nieukirk, S.L., and Fox, C.G. (2001). Geographic and seasonal variation of blue whale calls in the North Pacific. Journal of Cetacean Research and Management 3: 65–76.

Thode, A.M., D'Spain, G.L., and Kuperman, W.A. (2000). Matched-field processing, geoacoustic inversion, and source signature recovery of blue whale vocalizations. Journal of the Acoustical Society of America 107: 1286–1300.

Thompson, P.O., and Friedl, W.A. (1982). A long-term study of low frequency sounds from several species of whales off Oahu, Hawaii. Cetology 45: 1–19.

Tyack, P.L. (1986). Population biology, social behavior, and communication in whales and dolphins. Trends in Ecology & Evolution 1: 144–150.

Tyack, P.L., and Clark, C.W. (2000). Communication and acoustic behavior of dolphins and whales. In: W.W.L. Au, A.N. Popper and R.R. Fay (eds.): *Hearing by Whales and Dolphins*, pp. 156–224, Springer-Verlag.

Van Parijs, S.M., Clark, C.W., Sousa-Lima, R.S., Parks, S.E., Rankin, S., Risch, D., Van Opzeeland, I.C. (2009). Management and research applications of real-time and archival passive acoustic sensors over varying temporal and spatial scales. Marine Ecology Progress Series 395 : 21-36.

Wartzok, D., and Ketten, D.R. (1999). Marine mammal sensory systems. In J. E. Reynolds and S. A. Rommel (Eds.), Biology of Marine Mammals (pp. 117-175). Smithsonian Institution Press, Washington, D.C.

Watkins, W.A., and Schevill, W.E. (1977). Sperm whale codas. Journal of the Acoustical Society of America 62: 1485–1490.

Watkins, W.A. (1981). Activities and underwater sounds of fin whales. The Scientific Reports of the Whales Research Institute 33: 83-117.

Watkins, W.A., Tyack, P., Moore, K.E., and Notarbartolo di Sciara, G. (1987). *Steno bredanensis* in the Mediterranean Sea. Marine Mammals Science 3: 78-82.

Wiggins, S. (2003). Autonomous acoustic recording packages (ARPs) for long-term monitoring of whale sounds. Marine Technology Society Journal 37(2): 13-22. http://dx.doi.org/10.4031/002533203787537375

Zimmer, W.M.X. (2011). *Passive acoustic monitoring of cetaceans*. Cambridge University Press, Cambridge, U.K.

Justification

Approved: Dr. A.O. Debrot, Project Leader
Senior Scientist

Signature:

Date: 29 April, 2014