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A Review and Inventory of Fixed Autonomous Recorders for Passive Acoustic Monitoring of Marine Mammals

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Abstract

Fixed autonomous acoustic recording devices (autonomous recorders [ARs]) are defined as any electronic recording system that acquires and stores acoustic data internally (i.e., without a cable or radio link to transmit data to a receiving station), is deployed semi-permanently underwater (via a mooring, buoy, or attached to the sea floor), and must be retrieved to access the data. More than 30 ARs were reviewed. They varied greatly in capabilities and costs, from small, hand-deployable units for detecting dolphin and porpoise clicks in shallow water to larger units that can be deployed in deep water and can record at high-frequency bandwidths for over a year, but must be deployed from a large vessel. The capabilities and limitations of the systems reviewed herein are discussed in terms of their effectiveness in monitoring and studying marine mammals.

Key Words: passive acoustic monitoring, fixed systems, marine mammals, acoustic monitoring, mitigation, autonomous recorders

Introduction

Marine mammals live most of their lives under the ocean surface, out of view of humans. The difficulties inherent in studying the effects of human activities on these animals can be overcome only through the application of technology (Samuels & Tyack, 1999). Most species of marine mammals are acoustic specialists that rely on sounds for communication and navigational purposes. Scientists and engineers have developed passive acoustic-based technologies to detect and record sounds produced by marine mammals to more effectively study them.

In 1880, Pierre and Jacques Curie (1880a, 1880b) discovered that when mechanical pressure was exerted on a quartz crystal, an electric potential is produced. This finding enabled the development of the first device capable of listening to sounds underwater—passive acoustic monitoring (PAM), which was utilized during World War I. Since then, the development of PAM technology has made it possible for researchers to listen to, record, store, and analyze marine mammal sounds. However, up until the turn of the century, limitations in PAM technologies and methods available, as well as high costs, inhibited the development and application of passive acoustics for marine mammal monitoring. In addition, the technical expertise required to develop and apply these technologies was typically beyond that of most field biologists. The development of fixed autonomous underwater sound recorders (ARs) in the early 1990s greatly reduced the costs and expertise required to monitor marine mammal sounds for extended time periods. An AR is defined as any electronic recording device or system that acquires and stores acoustic data internally (i.e., without cable or radio links to a fixed platform or receiving station) on its own, without the need of a person to run it; is deployed semipermanently underwater (i.e., usually via a mooring, buoy, or attached to the sea floor); and is archival (i.e., must be retrieved after the deployment period to access the data).

Today, ARs can be easily deployed on the ocean bottom to record acoustic data for days, weeks, or even months at a time. These archival ARs must then be retrieved to download data for post-processing and analysis. This approach allows ARs to be deployed and retrieved by field personnel with a relatively limited amount of training or expertise, which frees up valuable time, resources, and funding.

ARs are most cost effective when used in extreme or remote locations where access is limited or difficult—for example, polar regions, the deep sea, and locations where travel distances are great or environmental conditions exist that are too harsh to conduct surveys from aboard research vessels (Mellinger & Barlow, 2003; Munger et al., 2005; Sirovic et al., 2009). ARs are also useful for detecting marine mammals in areas where the occurrence of animals is infrequent, or where ship-based surveys have a very high cost per detection (Mellinger & Barlow, 2003). The cost savings in the use of ARs is achieved because of their autonomous nature—that is, their operation is independent of the presence of a human operator. The disadvantage is that these instruments must be recovered to access the data; therefore, real-time monitoring is not possible. If archival data are useful, such as for acoustic prospecting efforts (i.e., during pilot studies), ARs should be considered as a cost-effective approach. In general, set-up and infrastructure costs are lower for ARs than they are for other types of PAM systems (e.g., fixed-cabled hydrophones, towed-hydrophone arrays, and real-time radio- or satellite-linked hydrophones; Mellinger et al., 2007a). In addition, ARs are more flexible in their configuration, timing, and location of deployment, and they are less obtrusive to both animals and vessel traffic when compared to other types of PAM systems. Still, acoustic data bandwidth and collection capabilities are usually higher for these other types of PAM systems than they are for ARs (Mellinger et al., 2007a; Van Parijs et al., 2009). These trade-offs must be considered when deciding which type of PAM system to use to reach a particular goal.

A critical view of state-of-the-industry AR technology is provided herein, including both "traditional" autonomous recording devices (i.e., those designed specifically for recording geophysical events, underwater noise, and marine animal sounds) and "nontraditional" recording devices (e.g., electronic animal tags such as acoustic dataloggers). A review of the history of AR development; their capabilities and constraints with respect to different application requirements (monitoring vs mitigation); specific environments in which they can be used, and, perhaps most importantly, the species to be monitored; and the biological questions that are to be addressed are presented herein. AR capabilities and constraints are discussed with respect to their use in monitoring marine mammals in relation to oil and gas exploration and production (E&P) activities.

Historical Overview of the Development of Autonomous Recorders

During the late 1960s, a change in spatial scale occurred in marine geophysical research when scientists focused their studies on earthquakes in smaller areas of the sea floor. This shift required higher accuracy and more precise geophysical instrumentation and led to the development of autonomous instruments called Ocean Bottom Seismometers (OBSs) for monitoring underwater earthquakes. OBSs were able to measure movements of the Earth's crust (Loncarevic, 1977). An OBS is designed to rest on the ocean floor and uses a sensor called a *seismometer* to take measurements. The seismometer is comprised of a heavy mass suspended on a spring between two magnets. Seismometers use the principle of inertia: the resistance of an object to a change in its state of motion. When the earth's crust shifts, the seismometer and its magnets move concurrently, but the heavy mass momentarily remains in its original position. The relative movements of the mass through the magnetic field produce electrical currents that are then measured by instrumentation in the OBS (Dorman, 2001; Ocean Instruments, n.d.).

A typical OBS consists of a seismometer, a data logger, batteries to power the device, weight to sink it to the sea floor, a remotely activated (or timed) release mechanism, and flotation to buoy the instrument back to the surface (Dorman, 2001; Ocean Instruments, n.d.). By 1975, the OBS became an operational tool used by a dozen or so research groups in at least seven countries (Loncarevic, 1977). Since then, OBSs developed by researchers from France, Japan, Australia, Germany, Russia, and the U.S. have been used extensively in geophysical research efforts.

Small ground motions caused by earthquakes have relatively higher frequencies, so monitoring them requires special short-period OBSs that can record motions up to hundreds of times per second (Ocean Instruments, n.d.). These higher frequency OBSs, originally intended to pick up the motion of the crust via the motion of the substrate upon which they rest, typically record up to 100 Hz and are also capable of recording low-frequency sounds produced by large baleen whales (e.g., blue whale [*Balaenoptera musculus*] and fin whale [*B. physalus*])—sounds that contain frequencies below 100 Hz. McDonald et al. (1995) were the first to use OBS data to study marine mammals: blue and fin whale calls were detected and localized in deep waters during a seismic study on the southern Juan de Fuca Ridge off the coast of Oregon. These data were recorded incidentally during a seismology experiment.

A similar device called an Ocean Bottom Hydrophone (OBH) is also used by geologists to study seismic activity in the ocean. An OBH has a hydrophone instead of (or in addition to) a seismometer. Experiments using both vertical seismometers and hydrophones have shown a higher signal-to-noise ratio for large whale low-frequency calls on seismometers than on hydrophones (McDonald et al., 1995), even though hydrophones are able to record higher frequencies than seismometers. Besides John Hildebrand's group at the Scripps Institution of Oceanography Whale Acoustics Lab (McDonald et al., 1995), Christopher Fox's group at the National Oceanic and Atmospheric Administration's (NOAA) Pacific Marine Environmental Laboratory (PMEL) has also used OBSs/OBHs to gather marine mammal data since the early 1990s (e.g., Stafford et al., 1999; C. W. Clark, pers. comm., 28 November 2009).

OBSs and OBHs were too expensive for most researchers to purchase in the quantities needed to study marine mammals, so during the 1990s, several laboratories started developing their own ARs in an attempt to lower the costs and to modify the design for their own needs. One example was a relatively small experimental instrument with a single hydrophone that was developed by John Orcutt at Scripps Institution of Oceanography (SIO). The low cost and smaller size of the Low-Cost Hardware for Earth Applications & Physical Oceanography (LCHEAPO) was the direct result of the availability of new, low-power consumer electronics. Different institutions were then collaborating in the deployment and testing of these instruments (C. W. Clark, pers. comm., 28 November 2009). An example was the collaboration between Peter Worcester's group at SIO and Cornell University during the monitoring of the ATOC (Acoustic Thermometry of Ocean Climate) transmissions on the Pioneer Seamount during humpback whale (*Megaptera novaeangliae*) research off Hawaii (Frankel & Clark, 1998) and during research on blue and fin whales off southern California (Clark & Fristrup, 1997; Fristrup & Clark, 1997).

Soon thereafter, John Hildebrand (SIO Whale Acoustics Lab), Christopher W. Clark (Bioacoustics Research Program [BRP] at Cornell University), and Haru Matsumoto (NOAA/PMEL) were among the first to develop and deploy their own ARs. Each group designed a different instrument specifically to collect bioacoustic data from marine mammals (Calupca et al., 2000; Wiggins & Hildebrand, 2007). Thus began the cultural transmission of oceanography to bioacoustics as some of these instruments (such as the Marine Acoustic Recording Units [MARUs] or pop-ups from BRP) were the direct result of researchers and engineers from these two areas of expertise, and from two different institutions (SIO and BRP), exchanging technology and knowledge to help create the initial design of that instrument (C. W. Clark, pers. comm., 28 November 2009).

More recently, advances in low-power electronics, high-capacity data storage, computer processing technology, and power supply units have enabled the development and use of ARs capable of monitoring the acoustic environment and behavior of many species of marine mammals. Improvements in electronic data storage and battery technologies have allowed data collection for much longer periods of time and at higher data-sampling rates than previously possible. These ARs will be reviewed below with examples provided related to their use in marine mammal research and monitoring.

Methods

An inventory of autonomous recorders was conducted between 2009 and 2012 by searching available systems online using the beta version of *Scientific WebPlus* (ISI Web of Knowledge), a Web-based search engine that is focused on scientific content, recent scientific developments, and other science-based information selected by Thomson Reuters editors. A search for the string in English "autonomous underwater sound recording" returned 149 results. Additional information included in scientific papers and reports and on commercial webpages was searched using the Google search engine (both the regular Web search and Google Scholar) and all relevant library databases available through Cornell University and the University of Hawaii. A request for information was sent to Bioacoustics-L and MARMAM listservers, which are commonly viewed by marine mammal researchers and bioacousticians and other professionals working on passive acoustic monitoring of marine mammals. Conference proceedings and abstracts were also reviewed for relevant information. Finally, researchers, organizations, and companies were contacted directly via e-mail to inquire about specific systems or devices.

Results

Inventory of Current Fixed Autonomous Recorders

Over 40 instruments were identified that fit the working definition of fixed autonomous acoustic recording devices used for marine mammal monitoring (Table 1). These included miniaturized recording devices (i.e., data-logger animal tags) that have been modified or can be implemented as fixed ARs (Au et al., 2000; Thode et al., 2006; Akamatsu et al., 2008; Arias et al., 2008).

Table 1. Inventory list of fixed autonomous acoustic recording (AR) devices, including acronyms, developers, and sources of information

Acronym	System name	Developers	References listed by date
AAR on a MFP or "Insta-array"	Autonomous Acoustic Recorder arranged as sensors in a Portable Matched-Field Processing System or "Insta-array"	Marine Physical Laboratory (MPL), Scripps Institution of Oceanography (SIO), Greeneridge Sciences, Inc., University of Queensland, and the Defence Science and Technology Organization, Defence Department of Australia	Thode et al., 2006
Acousonde™ 3A (tag) and Acousonde™ 3B (tag)	Replaced the Compact Acoustic Probe (CAP) or Bioacoustic Probe (Bio-probe)	Greeneridge Sciences, Inc.	Burgess et al., 1998, 2011; Au et al., 2000; Burgess, 2000; Insley et al., 2007; Oleson et al., 2007b; Acousonde, n.d.
ADIOS	NA	National Oceanic and Atmospheric Administration (NOAA) and Central Bering Fishermen's Association (CBSFA)	Ponce et al., 2012
AARS	Autonomous Acoustic Recording System	National Sun Yat-sen University, Kaohsiung, Taiwan	Ming-Hao et al., 2007
AHS, AUH, OBH, or Haruphone	Autonomous Hydrophone System, Underwater Hydrophone, or Ocean Bottom Hydrophone	NOAA Pacific Marine Environmental Laboratory (PMEL) and Oregon State University (OSU)	Stafford et al., 1999; Fox et al., 2001; Fowler, 2003; Mellinger et al., 2004a, 2004b, 2007; Nieukirk et al., 2004; Heimlich et al., 2005; Dziak et al., 2007
AQUAclick	NA	Aquatec Group Limited, Hampshire, UK	Kyhn et al., 2008; AQUATEC, n.d.
AMAR	Autonomous Multi-Channel Acoustic Recorder	JASCO Research Ltd, Canada	JASCO, 2009a, 2009b
AMAR G3	Autonomous Multi-Channel Acoustic Recorder Generation 3	JASCO Research Ltd, Canada	JASCO, 2012
ARP	Acoustic Recording Package	Scripps Institution of Oceanography Whale Acoustic Lab (SWAL)	Wiggins, 2003; Gedamke, 2005; Munger et al., 2005; Gedamke et al., 2007; Oleson et al., 2007a; Stafford et al., 2007; Wiggins & Hildebrand, 2007; Širović et al., 2009
A-TAG (tag)	Acoustic tag	Marine Micro Technology, Japan	Akamatsu et al., 2000, 2005, 2008, 2011; Wang et al., 2005; Kimura et al., 2009
AUAR	Autonomous Underwater Acoustic Recorder	V. I. Ili'chev Pacific Oceanological Institute in Russia	Acoustics, 2004; Borisov et al., 2008
AULS	Autonomous Underwater Listening Stations	Clifford Goudey, MIT Sea Grant, Center for Fisheries Engineering Research (CFER); Rodney Rountree, University of Massachusetts/Dartmouth; and Tony Hawkins, University of Aberdeen, King's College, UK	MIT Seagrant, n.d.; Discovery of Sounds in the Sea (DOSITS), 2011

Acronym	System name	Developers	References listed by date
AURAL-M2	Autonomous Underwater Recorder for Acoustic Listening Model-2	Multi-Electronique Inc., France (MTE)	Simard et al., 2008; Multi-Électronique Inc (MTE), 2012
AUSOMS-D	Automatic Underwater Sound Monitoring System	System Intech Co., Ltd, Tokyo, Japan	Shinke et al., 2004; Ichikawa et al., 2006; Tsutsumi et al., 2006
Crittercam (tag)	Video camera	Greg Marshall with support from National Geographic	Marshall, 1998; Calambokidis et al., 2007
DASAR	Directional Autonomous Seafloor Acoustic Recorders	Greeneridge Sciences, Inc. incorporated DIFAR sensors from Sparton Electronics, FL, into DASARs.	Norman & Greene, 2000; Greene et al., 2004; Blackwell & Greene, 2006; Blackwell et al., 2007, 2012; Greeneridge Sciences, n.d.
DSG-Ocean	Ocean Digital Spectrogram Recorder	Loggerhead Instruments	Loggerhead Instruments, 2012
DMON	Digital Acoustic Monitor	Woods Hole Oceanographic Institution (WHOI)	M. Johnson, pers. comm., 25 August 2008; A. Bocconcelli, pers. comm., 17 October 2009
DTAG (tag)	Digital Acoustic Tag	WHOI	Johnson & Tyack, 2003; Tyack et al., 2006; Arias et al., 2008
EAR	Ecological Acoustic Recorder	Marc O. Lammers, Oceanwide Science Institute (OSI), and Kevin Wong, NOAA Fisheries, Pacific Islands Fisheries Science Center, Coral Reef Ecosystem Division (CRED), Hawaii	Lammers et al., 2008
HARP	High-frequency ARP	SWAL	Wiggins & Hildebrand, 2007; Baumann et al., 2008
LARS-LF and -HF	Long Term Acoustic Recording Systems (Low and high frequency)	David Mann, University of South Florida (USF)	DOSITS, 2011
LADC EARS	The Littoral Acoustic Demonstration Center Environmental Acoustic Recording System	Naval Oceanographic Office (NAVOCEANO)	Newcomb et al., 2002, 2009; Ioup et al., 2009; J. Newcomb & G. Ioup, pers. comm., 30 November 2009
OAR (tag)	Onboard Acoustic Recorder	Stacia Fletcher, Department of Biology and Institute of Marine Sciences, University of California at Santa Cruz	Fletcher et al., 1996
OCEANPOD	NA	LADIN (Laboratório de Dinâmica e Instrumentação), Universidade de São Paulo, São Paulo, Brazil	LADIN, 2012
OCEANBASE	NA	LADIN, Universidade de São Paulo, São Paulo, Brazil	LADIN, 2012
PAL	Passive Aquatic Listener	University of Washington's Applied Physics Laboratory (APL); available commercially through RSL (Environmental Remote Sensing Technologies Ltd.) in Athens, Greece	Nystuen, 1998, 2006; Nystuen et al., 2007; J. Nystuen, pers. comm., 15 November 2008; Anagnostou et al., 2011

Acronym	System name	Developers	References listed by date
PANDA	Pop-up Ambient Noise Data Acquisition	Acoustic Research Laboratory (ARL) of Tropical Marine Science Institute in National University of Singapore	Koay et al., 2001, 2002
A-PANDA	Advanced Pop-up Ambient Noise Data Acquisition	ARL of Tropical Marine Science Institute in National University of Singapore	Koay et al., 2006
Pop-up or MARU	Marine Acoustic Recording Unit	Bioacoustics Research Program (BRP) at the Lab of Ornithology (CLO), Cornell University	Calupca et al., 2000; Clark et al., 2000, 2002; Sousa-Lima & Clark, 2008, 2009; T. Calupca, pers. comm., 14 January 2009
RASP	Registratore Acustico Subacqueo Programmabile	Nauta Ricerca e Consulenza Scientifica, Italia	NAUTA, n.d.
RUDAR™	Remote Underwater Digital Acoustic Recorder	Cetacean Research Technology	J. R. Olson, pers. comm., 1 February 2009; Cetacean Research Technology, 2012
µRUDAR™	Micro Remote Underwater Digital Acoustic Recorder	Cetacean Research Technology	J. R. Olson, pers. comm., 20 October 2009; Cetacean Research Technology, 2012
nRUDAR™	Nano Remote Underwater Digital Acoustic Recorder	Cetacean Research Technology	Cetacean Research Technology, 2012
SM2M	Song Meter Autonomous Submersible Recorder	Wildlife Acoustics, Inc., USA	Wildlife Acoustics, Inc., 2012
SM2M Ultrasonic	Song Meter Autonomous Submersible Recorder, Ultrasonic Version	Wildlife Acoustics, Inc., USA	Wildlife Acoustics, Inc., 2012
SRB-16	SRB-16 Autonomous Recording Buoy	High Tech, Inc., USA	High Tech, Inc., 2005
T-POD, C-POD, and DeepC-POD	NA	Chelonia Limited, UK	Watkins & Colley, 2004; Chelonia Limited, 2007, 2011, 2012, n.d.; Kyhn et al., 2008
USR	Underwater Sound Recorder	CMST (Centre for Marine Science and Technology), Curtin University, Australia	CMST, 2011
UTDRT (tag)	Ultrasound Time/ Depth-Recording Tags	Peter Madsen, Department of Zoophysiology, Institute of Biological Sciences, University of Aarhus, Denmark	Madsen et al., 2002

The instruments reviewed herein were in various stages of development. Some AR systems that were researched were in early stages of development and did not have detailed specifications available, or in some cases, a response to our direct attempts at contacting developers for further information was not received (e.g., the Digital Hydrophone from MarSensing Lda. in Portugal and the Autonomous Acoustic Recording System developed by Ming-Hao et al., 2007). Thus, it was not possible to provide complete, or in some cases any, information on some of these systems.

Instruments researched that have very limited application for passive acoustic monitoring were also not included in the inventory. An example is the system designed by Hayes et al. (2000): an "inexpensive animal recording and tracking system" (see also Møhl et al. [2001] for a similar passive location system). This system used autonomous sound-recording buoys deployed at several locations simultaneously to produce a sparse hydrophone array. Each buoy was an instrument that contained a global positioning system (GPS) location logger, a portable stereo digital audio tape (DAT) recorder with a hydrophone connected to one channel, and a VHF radio signal for time synchronization connected to the second channel. The authors point out that the main disadvantage of the system for PAM applications is the duration of the recordings. DAT tape recorders are capable of recording sounds for a maximum of 6 h (using a 90-m tape and setting the recorder to "long-play" mode at 32 kHz), which is not a long enough duration for most PAM applications. Note that the µRUDAR™ (Cetacean Research Technology, 2012), although also limited in recording duration (up to 61 h), uses a compact flash card as storage media which, along with solid-state hard drives, have mostly replaced DATs as portable recording devices. Therefore, Hayes et al.'s instrument is now considered outdated and is not further reviewed or included in Tables 1 and 2, but the µRUDAR™ is. In a number of cases, newer versions of the instruments included in this review are also being developed and are noted as such in Table 2.

Capabilities of Fixed Autonomous Recorders

ARs provide a cost-effective way to determine the presence, relative numbers, and distribution of vocalizing marine mammals in space and time. The capabilities of ARs that are necessary for monitoring marine mammals will vary according to the goals and biological questions, the sound production behavior of the species of interest, the environment in which the ARs are to be deployed, and the ambient noise characteristics. For example, monitoring the seasonal occurrence of baleen whales usually requires deployments of several months to a year. However, because baleen whales produce low-frequency sounds with good propagation characteristics, the requirements for spatial coverage and sample rates are relatively low (usually less than 1 kHz; Wiggins, 2003) compared to those that would be required to monitor most species of odontocetes (at least 48 kHz; Oswald et al., 2004) over a similar area. Low sample rates required to record low-frequency sounds also allow modest power and storage capabilities for the AR.

In general, odontocetes produce mid- (whistles between approximately 5 and 25 kHz) to high-frequency sounds (pulsed clicks containing energy well above 20 kHz) that do not propagate as well as the sounds produced by baleen whales (Richardson et al., 1995). This is because higher frequencies attenuate more rapidly (Bradbury & Vehrencamp, 2011). In addition, the pulsed signals produced by odontocetes often have very narrow beam patterns and so are more difficult to detect when animals are not on axis relative to the hydrophone. Because the sounds produced by marine mammals cover such a large frequency range, different AR deployment strategies must be considered for different species. For example, in order to monitor odontocete echolocation clicks, an area must be relatively densely covered with ARs that have high sampling rates (e.g., harbor porpoises [*Phocoena phocoena*]; Kyhn et al., 2008), while a sparse population of ARs that have low sample rates are required to monitor low-frequency sounds such as those produced by baleen whales (e.g., Sousa-Lima & Clark, 2008, 2009). How should a user choose an AR system? First, the questions and goals to be addressed for a given study must be clearly defined and considered. This will, in turn, dictate the requirements of the AR system. Based on the costs, capabilities, and specifications of an AR system, as well as deployment and retrieval issues related to the monitored area, the user may then consider the options available. For example, suppose the scientific question of interest concerns the effects of oil and gas E&P activities on the spatial distribution of singing humpback whales on their breeding grounds during winter when animals are singing for many hours continuously. Addressing this question will require multiple time-synchronized ARs that can be deployed close enough to each other so that each AR can record the same sounds for multiple whales to allow localization and tracking of multiple animals for 3 to 7 mo, sampling at relatively low frequencies (1 to 2 kHz). If sampling schemes are available (i.e., recordings made at predefined intervals), the AR can be programmed to record on a duty cycle of 30 min on, 30 min off, for example

Table 2. Summary of the main capabilities and specifications of each AR system (NA = information not available)

Instrument	Dimensions	Maximum deployment depth (m)	Maximum deployment time	Sampling frequency (Hz)	Power supply and energy capacity	Data storage	Data format	Microprocessor	Examples of species studied
AAR	20 × 2.5 cm for each recorder	2,000	71 h	2,000 (100-20,000)	Alkaline battery pack	1 GB flash memory	MT files, depth, tag temperature 2-D acceleration/tilt	NA	*Megaptera novaeangliae*
AARS	NA	NA	4.5 h	69,000	16 V lithium cells	Hard disk	NA	PC-104 single-board computer (Celeron 1G)	NA (tested in the field with noise)
Acousonde™ (tag)	22.1 × 3.2 cm	3,000	23 d (at 2 kHz)	25,793 (low-power channel) 232,000 (high-frequency channel)	Lithium battery pack	8 GB	2 acoustic channels, MT files, depth, tag temperature 2-D acceleration/tilt (option)	Tattletale Model 7 on earlier version (Bioacoustic probe)	*M. novaeangliae*, *Mirounga angustirostris*
Acousonde™ 3A (tag) and Acousonde™ 3B (tag)	22.1 × 3.2 cm 22.4 × 4.2 cm	3.000	14 d	22 (low-frequency channel) 232,000 (high-frequency channel)	A-cell lithium battery pack	16 GB internal memory and 4 MicroSD storage-card slots; 16 GB internal memory and 2 MicroSD storage-card slots	2 acoustic channels, MT files, depth, tag temperature, 3-D acceleration/tilt, ambient light level	ARM9 with an ARM vector floating point (VFP) coprocessor (www.arm.com) 208 MHz	NA
ADIOS	12 cm diameter × 75 cm long	100	7 d	100,000	D-cell batteries	128 GB	NA	Persistor CF2	*Eschrichtius robustus*, *Physeter macrocephalus*
AHS, AUH, OBH, or Haruphone	1.8 × 0.17 m	4,000	1 y 14 d	100 900	Alkaline battery pack	4 GB hard drives	Spectrograms	NA	*Balaenoptera edeni*, *B. musculus*, *B. physalus*, *B. acutorostrata*, *Eubalaena glacialis*, *M. novaeangliae*, and other non-identified baleen whales

Instrument	Dimensions	Maximum deployment depth (m)	Maximum deployment time	Sampling frequency (Hz)	Power supply and energy capacity	Data storage	Data format	Microprocessor	Examples of species studied
AQUAclick	240 mm long × 88 mm diameter	100	Until storage capacity is reached	50,000-170,000	NiMh rechargeable batteries	8 MB standard memory	Click parameters stored are occurrence time, duration, and sound level	NA	*Phocoena phocoena*
AMAR	Standard: 71.1 × 17.8 cm; 36.4 kg	400	50 d	Up to 128,000	Alkaline or lithium batteries	Solid-state storage. 128 GB base, expandable to 2 TB or more	1-2 channel WAV files with non-acoustic data (Temperature and 3-axis orientation are standard; high-precision orientation; ADCPs; turbidity; depth; or any other analog, RS-232, or RS-485 system on request.)	NA	*B. physalus*, *Balaena mysticetus*, *Eschrichtius robustus, Orcinus orca, Delphinapterus leucas*, *Odobenus rosmarus*, *Erignathus barbatus*
AMAR G3	132.1 × 40.4 cm; Diameter: 16.5 cm	250 (shallow AMAR) 2,500 (deep AMAR)	1 y dependent on input channel configuration, duty cycle settings, and attached battery packs	1-150,000	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 1,796 GB	Acoustic data as WAV formatted files; non-acoustic data as CSV files	NA	NA
ARP	1.5 m by 1.5 m by 1.5 m plus a 10-m long line and flotation for the hydrophone	Up to 7,000	~ 400 d	1,000	Alkaline or lithium battery pack	72 GB hard disk drives	Time series, spectra, or spectrograms	Ocean Sensors OS500 data logger (www.oceansensors.com) 20 MHz	*B. musculus*, *B. physalus*, *B. bonarensis*, *M. novaeangliae*, *Eschrichtius robustus*, *Balaena mysticetus*, *Eubalaena japonica*

Instrument	Dimensions	Maximum deployment depth (m)	Maximum deployment time	Sampling frequency (Hz)	Power supply and energy capacity	Data storage	Data format	Microprocessor	Examples of species studied
A-tag (tag)	21 mm diameter and 108 mm length	200	75 d	55,000-235,000	Lithium battery cell	128 MB flash memory	Click intensity, timing, and the difference in time arrival between two hydrophones	CPU (PIC18F6620; Microchip, Detroit, MI, USA)	*Neophocaena phocaenoides asiaeorientalis*
AUAR **	Weight = 145 kg	50	30 d	15,000	Three sealed gel batteries with a capacity of 115 Ah	Records data on a 1 GB flash disk then writes it onto a 160 GB hard drive	Analog sound data	*Prometheus* single board PC/104 computer manufactured by Diamond Systems Corporation	*Eschrichtius robustus*
AULS	NA	200 or 1,800 (not tested)	57 h	11,000-44,000	Lead-acid gel cells	10 GB hard drives	WAV files	NA	Fish
AURAL-M2	With 16 batteries: 14.6 × 90 cm and 20 kg; with 64 batteries: 14.6 × 120 cm and 32 kg; with 128 batteries: 14.6 × 178 cm and 49 kg	300	1 y depending on setting parameters	256-32,768	Alkaline D-cell or battery pack	Compact flash 1 GB or more and 2.5" hard disk 320 GB or more	WAV files, temperature and depth	33 MIPS Dallas DS89C450 Ultra High Speed Flash Microcontroller	Whales in the St Lawrence River
AUSOMS-D	NA	NA	NA	44,100	NA	NA	2 acoustic channels	NA	*Dugong dugon*
C-POD	660 mm length × 90 mm diameter; 2.1 kg without batteries, 3.55 kg with batteries	At least 100 m	4 mo	20,000-160,000	Alkaline battery pack	Two removable 4 GB SD cards	Click center frequency, frequency trend, duration, intensity (8 bit), bandwidth, envelope slope, angle of the POD to the vertical, and temperature	Altera MAXII	All odontocetes except sperm whales (*P. macrocephalus*)

Instrument	Dimensions	Maximum deployment depth (m)	Maximum deployment time	Sampling frequency (Hz)	Power supply and energy capacity	Data storage	Data format	Microprocessor	Examples of species studied
DeepC-POD	680 mm length × 100 mm diameter; 5.5 kg without batteries, 6.96 kg with batteries	At least 2,000 m	4 mo	20-160,000	Alkaline battery pack	Two removable 4 GB SD cards	NA	NA	All odontocetes except sperm whales (*P. macrocephalus*)
DASAR	Cylinder of 30 by 36 cm	30	45 d	2,400	Alkaline battery pack	30 GB disk drive	3 channels provide azimuthal bearings to sound sources	Persistor Instruments Inc. (Bourne, MA, USA) single-board computer, model CF1 with a Persistor Instruments BigIDEA IDE controller	*Balaena mysticetus*
DSG-Ocean	11.4 cm diameter × 63.5 cm PVC: 3.6 kg in air (no batteries); 2.9 kg positive in seawater; weight of 3 D cells = 454 g Aluminum: 7.8 kg in air (no batteries); ~1.4 kg negative in seawater	100 m for PVC housing and 2,000 m for aluminum housing	Calculated by proprietary software during set-up based on memory size and recording schedule	80,000 burst recordings of up to 400,000	Alkaline battery pack 8 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	dsPIC33F	Invertebrates, fishes, and marine mammals
DMON	70 mm (7.1 cm) diameter × 215 mm (21.6 cm) Weight (air): 1.5 kg Weight (salt water): 400 g	1,500	LF 50 d MF 180 h	Examples of three possible frequency settings: LF 80,000 MF 240,000 HF 480,000	Rechargeable Li-Ion battery	32 GB flash memory * * *	Sound files (3 independent acoustic channels), temperature, depth, and orientation	TMS320VC5509A DSP	Fish and cetaceans

Instrument	Dimensions	Maximum deployment depth (m)	Maximum deployment time	Sampling frequency (Hz)	Power supply and energy capacity	Data storage	Data format	Microprocessor	Examples of species studied
DTAG (tag)	5 × 12 cm (attached to a GPS equipped buoy)	2,000	Determined by its memory capacity and audio sampling rate	2,000-20,000	Lithium battery	3.3 or 6.6 GB flash memory	Sounds, depth, temperature, and orientation	NA	*Eubalaena glacialis*, *P. macrocephalus*, *beaked whales*
EAR	10.16 cm diameter by 60 cm long cylinder	500	1 y	2-64,000 (max)	Alkaline battery pack	Flash memory card periodically transferred to a hard drive	Binary files	Persistor CF2 microprocessor, a 1 GB compact flash card, a Persistor BigIDEA IDE adapter	*Stenella longirostris*
HARP	Six 30.5-cm diameter glass spheres plus a 10-m long line and flotation for the hydrophone	~7,000	55 d OR 1 y	10-200,000 OR 30,000	Alkaline or lithium battery pack	16 high-capacity integrated drive electronics (IDE) laptop disk drives	XWAV time series files	32-bit, 20 MHz microcontroller from Motorola (www.motorola.com)	*Tursiops truncatus*, *Stenella longirostris*, *Peponocephala electra*, *Mesoplodon* sp.
LARS-LF and LARS-HF	NA	NA	1 y 2 mo	3,333 44,100	NA	Flash memory	NA	NA	Fish and dolphins
LADC EARS	21.6 cm in diameter and 61.9 cm long; 45.5 kg	3,000	14 d at max sampling frequency >66 d at 11,700 Hz sampling frequency	50-192,000 (max)	Alkaline D cells	4 IDE 2.5" disk drives	NA	NA	*P. macrocephalus*
OAR (tag)	17.08 × 12.70 × 6.67 cm	800	6 d	20-14,500	Alkaline batteries	Digital audiotape (DAT recorder)	Sound files	NA	*Mirounga angustirostris*, *Zalophus californianus*
OceanPod	11 × 45 cm	70 for PVC 1,000 m for aluminium	23 d	48 or 96 kHz	Alkaline D cells	32 GB	PCM, MP3	NA	Cetaceans, fish, sea state, and vessels

Instrument	Dimensions	Maximum deployment depth (m)	Maximum deployment time	Sampling frequency (Hz)	Power supply and energy capacity	Data storage	Data format	Microprocessor	Examples of species studied
OceanBase	9 × 45 cm	70 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	Depending on user's application	SSD 128 GB expandable to 1 TB or more	PCM, MP3; non-acoustic signals in CSV format	ARM platform	Cetaceans, fish, sea state, and vessels
PAL	76.2 cm long × 15.2 cm in diameter	1,000	1 y	0-50,000	Alkaline D cells	2 GB flash memory card	Binary restored to time series (sound bites)	Tattletale Model 8	*Orcinus orca*, dolphins
PANDA	30 kg without anchor	200	9-10 d	10-10,000	Rechargeable lithium video camera batteries	12 GB hard drive	Time series	Persistor-based MCU system with processing power of an 80386 CPU	NA
A-PANDA	30 cm diameter × 70 cm long	200	35 h	10,000-150,000	Custom Li-Ion battery pack	40 GB hard disk	Direction of arrival estimations, time series	PC104+ stack that consist of an Intel Pentium III based industrial PC, a 40 GB hard disk, and a PC104 data acquisition module	NA
Pop-up or MARU*	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 dependent) Up to 6,000 (on moorings)	90 d	2,000-64,000 (max)	Alkaline battery pack (Double-bubble configuration doubles power capacity.)	120 GB hard drive	Binary restored to sound files (aiff)	Tattletale Model 8 and analog to digital conversion board made by Onset Technologies	*B. musculus*, *B. physalus*, *B. bonarensis*, *M. novaeangliae*, *Eubalaena glacialis*
RASP	9 × 50 cm	500	184 h maximum	Up to 96,000	Battery pack NiMH fast rechargeable	4 GB compact flash cards (8 GB available)	WAV or MP3 files	Modified MicroTrack 24/96 pocket recorders with an original time control board	Whales and dolphins
RUDAR™	17.8 cm, 36.4 kg or 45.5 kg with batteries	1,500 or 3,500	Depends on sample rate chosen	Selectable sampling rates up to 192,000	Rechargeable Li-Ion batteries	Compact flash cards for short deployments and hard disks for longer deployments	Up to 4 hydrophone channels, WAV	Sound Technology ST1400ENV_mobile data recorder and sound level monitor	Cetaceans

Instrument	Dimensions	Maximum deployment depth (m)	Maximum deployment time	Sampling frequency (Hz)	Power supply and energy capacity	Data storage	Data format	Microprocessor	Examples of species studied
µRUDAR™	33 cm long × 10 cm diameter	100	Up to 61 h depending on sample rate chosen	96,000	Rechargeable Li-Ion batteries	16 GB industrial-grade compact flash memory card	Up to 4 hydrophone channels, WAV or MP3	M-Audio MicroTrack II digital recorder	Cetaceans
nRUDAR™	NA	100	Up to 26 h depending on sample rate chosen	96,000	NA	NA	NA	NA	NA
SM2M	16.5 cm diameter × 79.4 cm long	150	Up to 104 d depending on sampling rate and duty cycle	4,000-96,000	LSD NiMH, alkaline, or lithium manganese D-cell batteries	128 GB with SDHC or 512 GB with SDXC	RMS level, SPL receive levels	NA	NA
SM2M Ultrasonic	16.5 cm diameter × 79.4 cm long	150	Up to 42 d depending on sampling rate and duty cycle	4,000-384,000	LSD NiMH, alkaline, or lithium manganese D-cell batteries	128 GB with SDHC or 512 GB with SDXC	RMS level, SPL receive levels, with optional Hi-SPL	NA	NA
SRB-16	NA	3,049	72 h and standby mode of up to 15 d	Dynamic range to suit user's application	Internal battery pack	5 GB recorded on Exabyte 8500 digital tape	NA	RS-232 navigation interface	NA
T-POD	Length: 0.86 m Diameter: 0.90 m; 2.8 kg with no batteries; 4.4 kg with 15 alkaline D cells	Center opening: 150 Deep water: 2,500 (tested), 3,500 (not tested)	1 y OR until storage capacity is reached	200,000	Alkaline battery pack	128 MB memory	Click start and end times, battery voltage, angle of the POD to the vertical, system noise, and temperature	Altera MAXII	*Phocoena phocoena*
USR	114 × 900 mm, weight = 30 kg (size options are available)	NA	2 y	1,000-15,000	NA	One or two 2.5" hard disk drives (60 GB to 160 GB) and/or Type 1 compact flash card	1 or 2 hydrophone channels; FAT32 files	NA	Fish, marine mammals, and noise
UTDRT (tag)	NA	1,100	30 min	62,500	NA	192 MB compact flash card	Sound files, real time and depth	Maxim Integrated Products, Inc. DS5000T	*P. macrocephalus*

* New versions or capabilities are in development.

** The information given here is for a radio transmitting version of the AUAR: T-AUAR (Borisov et al., 2008).

*** 64 GB capacity possible in 2010 (M. Johnson, pers. comm., 25 August 2008) (e.g., if analysis time is a constraint). This will save on power, storage, and post-processing requirements. The minimum number of units required and their deployment geometry are related not only to the species of interest and research question but also to the sound propagation profile of the area. The farther sound travels, the fewer the number of AR units that are needed to cover an area (the maximum number of units is usually limited by budget). Humpback whale breeding grounds are typically shallow (< 100 m); therefore, the depth rating requirement of the AR can be relatively modest. Other issues, such as high fishing activity or the presence of pirates in the area, the type and availability of deployment/retrieval vessels, and the amount of funding available, will all affect the best choice for an AR device.

Choosing an AR system will likely not be as simple as this example. If the question was "What is the diversity and relative occurrence of odontocetes in an area?," high sampling rates would be required, which, in turn, would limit deployment duration for continuous recordings. There are three main requirements for the data acquisition electronics to provide long-term continuous acoustic records of identifiable odontocete calls using an autonomous instrument: (1) low power, (2) high-speed digitization, and (3) high-capacity data storage (Lammers et al., 2008). As with any battery-powered autonomous instrument, low-power components are essential for long-duration deployments. High-speed digitization is necessary to record broadband odontocete calls and to provide enough bandwidth for species identification (upper bandwidth limit of at least 24 kHz for *Delphinus delphis, Stenella attenuata, S. coeruleoalba*, and *S. longirostris*; Oswald et al., 2004). High-speed digitization coupled with long-duration recordings requires high-capacity data storage capability (Wiggins & Hildebrand, 2007) and/or the use of a duty cycle recording schedule. In most cases, high-capacity data storage is achieved using multiple hard or flash drives, which require a microcontroller and firmware dedicated to controlling the data-recording process (e.g., HARPs; Wiggins & Hildebrand, 2007). These capabilities are important to understand when choosing the best AR available for a particular application.

Tradeoffs Among Fixed Autonomous Recorder Capabilities and Limitations

ARs have self-contained power supplies and data acquisition and storage electronics. These components constrain the design and capabilities of AR systems because of tradeoffs among power supply, data storage capacity, required sampling frequency, and instrument size and depth rating, which, in turn, effect cost and deployment duration. Each AR developer presents a different solution to manage these capability tradeoffs, and the resulting compromises are critical to selection of an AR system for application during any passive acoustic study—for example, oil and gas or other E&P-related activities or aquatic animal behavior, distribution, or presence research. The main limitation on deployment duration is sampling frequency, which is directly linked to storage and battery capacity. Increased power requirements have a direct effect on the number, and possibly type, of batteries included in a package, thereby potentially increasing both instrument size and flotation requirements. The size of the package will effect costs related to deployment and retrieval.

Figures 1 and 2 illustrate the tradeoffs among AR capabilities and how these influence each other; for example, given that the size of the device housing dictates the amount of power, when going from less to more power (bigger, more expensive housings), one can increase the sampling frequency to record higher-frequency sounds, which requires greater data storage capacity at the expense of deployment and recording duration. The more hydrophones on a unit (may enable localization/directionality capabilities, e.g., AUSOMS-D and DASAR), the greater the data storage requirement, which will impact deployment duration and increase the number of batteries needed. Systems that can be deployed to greater depth are usually more expensive because of the need for special pressure-resistant housings; thus,

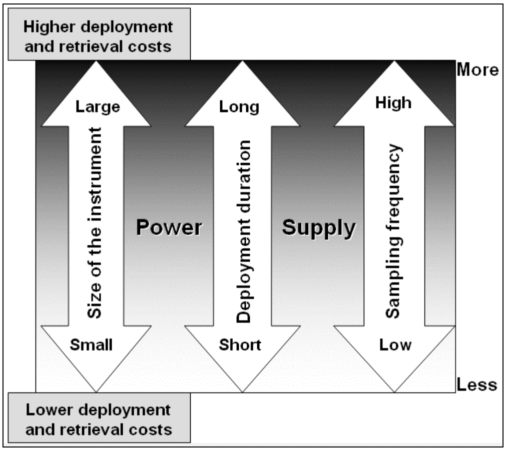

Figure 1. Schematic of the tradeoffs among power supply, sampling frequency, deployment duration, size and deployment, and retrieval costs; less power supply will limit AR sampling frequency and deployment duration but, in turn, will result in a smaller instrument package and decrease deployment and retrieval costs.

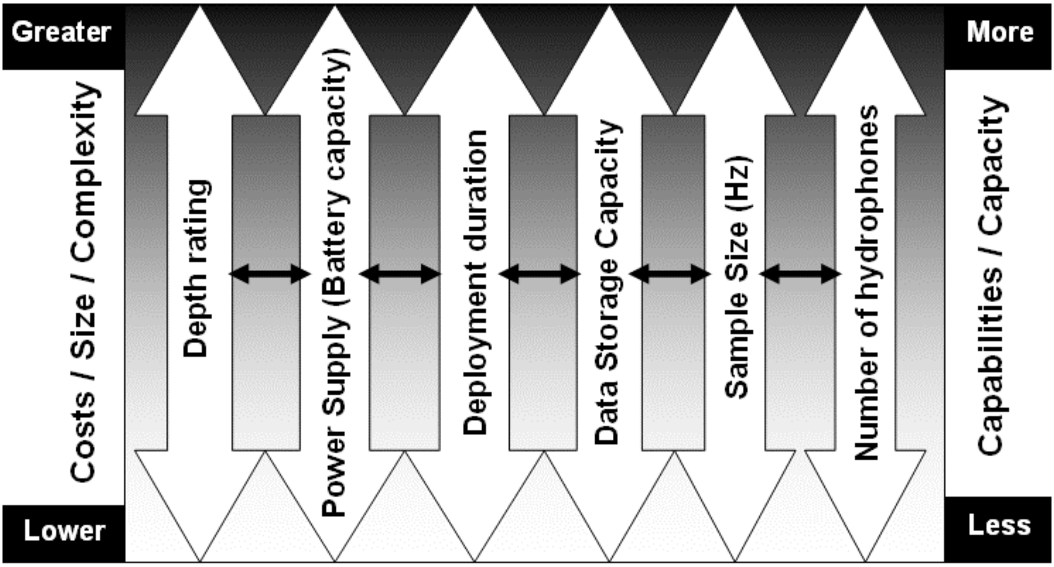

Figure 2. Schematic of more tradeoffs among capabilities and limitations of AR systems

as size and complexity of a system are increased, budgetary demands also generally increase.

Instruments like the HARP (Wiggins & Hildebrand, 2007; Table 2) provide high sample rates and good storage capacity (1.92 TB), which allows for approximately 55 d of continuous sampling at 200 kHz or about 1 y continuously sampling at a lower sample rate of 30 kHz. The HARP package is quite large because of associated battery and storage requirements, and it comes with a depth rating of 7,000 m (requiring a high pressure capable housing; Table 2). Note that the HARP package has been reduced in size for other applications such as deployments on gliders (Wiggins et al., 2010). To deploy large HARPs, a relatively large (> 24 m) oceanographic ship or mid-sized fishing vessel with winch and A-frame is required. These deployment and retrieval costs must be considered when planning to use HARPs.

Proportionately, the components that use the greatest amount of system power in ARs include the hard disk drive and hard drive controller (e.g., on HARPs). The data acquisition rate is indirectly related to power consumption because it determines how frequently the hard disk will need to be accessed and written to; for example, in Cornell BRP's pop-up, the digital acoustic data are temporarily saved to a buffer which, once filled, downloads to a hard drive. Data recorded at a sampling frequency of 2 kHz fill this buffer every 3 min, requiring access to the hard drives and, therefore, power consumption each time data are transferred. The hard drive runs for 6 s every 3 min when data writing is occurring. The standard battery pack will keep the unit recording continuously for a little over 100 d at the 2 kHz sample rate. At a 4 kHz sample rate, the data storage buffer will fill every 1.5 min, and the drive will have to run twice as often as at a 2 kHz rate, dropping the standard battery life to 50 d. At 6 kHz, the buffer fills every 45 s, and the efficiency of shutting down the hard drive between data writing sessions is lost so that it runs continuously to record the data flow, dropping battery life to about 22 d (T. Calupca, pers. comm., 14 January 2009).

Hard drive space may become a limiting factor in pop-ups at sample rates greater than 20 kHz (T. Calupca, pers. comm., 14 January 2009; Table 3). The standard pop-up hard drive stores 120 GB of data; therefore, at high sampling rates, data storage capacity, as opposed to power supply, can limit AR monitoring duration. The shift from hard drives to high storage capacity flash cards will take care of this limitation. The HARP, which can sample at 200 kHz, has a much larger storage capacity (1.92 TB) than pop-ups; the standard power configuration (estimated at 330 Amp-hours using 192 D-size alkaline batteries), recording continuously at the maximum sample rate, fills the hard disks before battery capacity is reached (Wiggins & Hildebrand, 2007).

The type and size of storage media influences tradeoffs as discussed above and, consequently, costs. In the last few years, solid-state flash memory has dropped significantly in price and increased in capacity, offering an alternative to hard drives that are bigger and heavier.

Continuous Recording vs Sampling Schemes (Duty Cycles)

When determining what type of sampling scheme or duty cycle to use, it is important to have an idea about the acoustic behavior of the target species to be monitored. Notably, being aware of the frequency range of the target species and also timing of calling activity will inform AR decision(s), although these acoustic characteristics may not be known before AR deployment. For many preliminary PAM applications, continuous recording is desirable because complete information about the acoustic behavior of animals and their acoustic environment is often lacking; the continuous record provides a more in-depth view of the animals' vocal activity in the context of environmental noise. Initially, medium- to long-term acoustic prospecting must be completed to determine what species are present, what types of sounds they produce, and how often they are produced; however, the amount of data generated by continuous recordings is typically excessively large (1 y may result in over 2 TBs of data at sampling rates under 2 kHz) such that automatic detection or sampling schemes must be applied during post-processing and analysis. This tradeoff between minimizing the nonsampling period and maximizing the time periods during which data are collected must be considered in relation to monitoring requirements and temporal aspects of the acoustic behavior for species in question. For example, a sampling scheme of 12 h on and 12 h off per day would not provide adequate coverage to examine whether a diel calling pattern is present from a particular species (Wiggins & Hildebrand, 2007; Lammers et al., 2008). Alternatively, a duty cycle of 5 min on/5 min off would be more appropriate to investigate for diel patterns in vocal behavior; a duty cycle like this would also reduce power consumption and facilitate longer duration monitoring.

Note that using an intermittent duty cycle is not well-suited for capturing acoustic signals that are very infrequent or random, but it is effective for documenting potential patterns of occurrence for regularly occurring signals typical of some species. For example, humpback whales, which sing continuously for several hours at a time during the breeding season, have been monitored using the EAR (Ecological Acoustic Recorder) at 3.3% duty cycle (i.e., recording once every 15 min for 30 s; Lammers et al., 2008). Continuous acoustic recordings can be useful when the aim is to compare other phenomena present in the recordings over time (e.g., Northern right whale [*Eubalaena glacialis*] call characteristics; Parks et al., 2007) or space (e.g., humpback song comparisons across regions; Cerchio et al., 2001; Darling & Sousa-Lima, 2005). Alternatively, triggering algorithms that only record the sounds of interest or record any sound at preset time intervals also can be advantageous. This approach involves periodic sampling with the ability to turn "on" the recording device when signals of interest occur. This method is desirable from both cost and data management standpoints (Lammers et al., 2008); however, such sampling requires validation to confirm that signals of interest are not missed by the algorithms used, and that the vocal behavior or call types of interest are well known.

Some systems (e.g., PAL, T-POD, C-POD, A-TAG, EAR, and AQUAclick; Tables 1 & 2) have automatic call detection algorithms that trigger recording when predetermined call types are detected, or when defined acoustic criteria are met. The PAL (Nystuen, 1998, 2006; Nystuen et al., 2007), the EAR (Lammers et al., 2008), and the DMON (M. Johnson, pers. comm., 25 August 2008) pre-process the data based on knowledge of the sound of interest, saving storage space and power. "Plug-in" user-supplied automatic detection algorithms can be used to automatically process, extract, and store particular parts of the sounds of interest (DMON). The PAL works with a satellite communication system that transfers data every 3 h to the surface. This includes variables such as wind speed, rainfall, bubble populations, whale and human activities, and even geological activities. Identifying correctly all these different sound sources is possible due to a classification algorithm that differentiates spectral and temporal characters of each detection (Anagnostou et al., 2011).

Even more specific are the click detectors/loggers, such as the AQUAclick (includes a porpoise channel tuned to 130 kHz and a "dolphin" channel at 50 kHz; AQUATEC, n.d.), the T-POD (Watkins & Colley, 2004) and C-POD (Chelonia Limited, n.d.a), and the A-TAG (Akamatsu et al., 2008), which do not record sounds but rather capture information associated with the sounds such as time of occurrence of high-frequency odontocete clicks. Nevertheless, if the sounds of interest are too variable, which is the case for many marine mammal monitoring applications, this advantage is diminished.

Future HARP systems are planned to implement such triggering algorithms in the data loggers, resulting in much smaller quantities of recorded data (Wiggins & Hildebrand, 2007). While this approach seems reasonable, the drawback is that nontargeted calls and other sounds of potential interest would go unrecorded. For example, dolphin and pinniped sounds would not likely be recorded by an algorithm designed to detect low-frequency baleen whale calls. Furthermore, investigating the structure and variability of ocean acoustic noise over various time periods would be difficult, if not impossible, using event-triggered acoustic data (Wiggins, 2003). Data compression schemes provide some means for decreasing power consumption rates while increasing deployment duration (Wiggins & Hildebrand, 2007). These approaches should be thoroughly tested so that recording fidelity is not compromised and the chosen algorithms match the objectives of the deployment.

Capability of Collecting Non-Acoustic Oceanographic Data

Some ARs integrate additional sensors to collect non-acoustic oceanographic data (Table 2). For example, the AMAR (JASCO, 2009a) collects data on water temperature and 3-axis orientation but also includes other sensors on request depending on the research questions under study. A small, self-contained, external CTD data logger or sound velocity sensor are planned as new add-ons to the PANDA (Koay et al., 2002; Tables 1 & 2). With the combined recordings of conductivity, temperature, pressure, sound velocity, and acoustic signals in a single integrated, compact system, PANDA is very useful for shallow-water physical oceanographic studies (Koay et al., 2001). Sound speed data are important for accurately calculating sound time-of-arrivals when using multiple ARs to localize the source of a sound.

Miniaturized electronic devices (animal tags) can be used as sensors and data loggers in fixed ARs. Several types of electronic tags have been used in fixed ARs; for example, Thode et al. (2006) used slight modifications of an older version of the Acousonde (Acousonde, n.d.; Burgess et al., 1998; Burgess, 2000) in designing the AAR (Tables 1 & 2). The Acousounde is a sound-recording animal tag with two acoustic channels that can sample up to 232 kHz, includes depth and internal temperature sensors, and can also contain 2-D acceleration/tilt sensors. The A-TAG has been used to tag and study finless porpoises (*Neophocaena phocaenoides*; Akamatsu et al., 2008) and is yet another example of tag technology that has been used in a fixed configuration (Wang et al., 2005).

The DTAG (Johnson & Tyack, 2003), a digital acoustic recording tag, contains an accelerometer, a magnetometer, and pressure sensors. It is designed to measure the tagged animal's orientation and sample sounds between 2 and 200 kHz (Johnson & Tyack, 2003). The DMON is a fixed AR used by the same group at Woods Hole Oceanographic Institution (WHOI) that is also capable of acquiring depth, temperature, and orientation data (A. Mooney, pers. comm., 26 November 2012).

Tags provide the capability to record oceanographic data, animal orientation, and other information and have been used to study several aspects of the behavior of a variety of species. All of the tags listed (Tables 1 & 2) also are able to collect sound data and could potentially be used in a fixed AR configuration for PAM applications.

Internal Design of Autonomous Recorders

ARs typically include a robust pressure housing to protect the electronics, digital recording systems, and batteries. An ideal AR requires high-quality sensors and low-noise electronics with a high-resolution digital recording system. The AR internal design and external package configuration should be based on the specific questions and objectives the system is built to address.

Electronics—Each AR developer has identified different solutions in their system designs. Still, all systems include a single or multiple hydrophone(s) for sound acquisition, internal electronics to control the system and for acoustic data conditioning (e.g., signal amplifiers, anti-aliasing and band-pass filters, and analog-to-digital converters), storage (e.g., hard drives, flash memory cards, and solid-state drives), and, often, additional electronics or devices (e.g., acoustic release mechanisms) to allow for recovery of the device.

Pop-up developers designed their system with the objective of creating a compact device that could be deployed by a single person to depths up to 2,500 m using an acoustic release. Therefore, a pop-up includes additional recovery electronics to enable retrieval, but also an acoustic command recognition system, an audio signal communications system, a fail-safe time-release mechanism, a radio beacon, and a strobe light (T. Calupca, pers. comm., 14 January 2009). The pop-up electronics are distributed on two plates that are housed within a borosilicate glass sphere, which is placed within a protective plastic helmet with the hydrophone and piezoelectric speaker mounted externally on its side (T. Calupca, pers. comm., 14 January 2009).

The DMON electronics configuration includes two circuit boards. The main board contains a digital signal processor, memory, power supply, and interface circuits. The sensor board contains sound acquisition circuits and depth and orientation sensors. This set of two boards can be used inside a pressure housing (e.g., a profiling float or glider that requires hydrophone[s] be wired to a penetrator) or it can also be used in a pressure-equalized housing (e.g., sealed in an oil-filled soft rubber sleeve) that can be deployed alone or in the wet space of an underwater vehicle (all sensors can be internal for protection and durability; M. Johnson, pers. comm., 25 August 2008).

High-capacity data storage is desirable for some applications (e.g., long-term, continuous monitoring of species that emit high-frequency sounds). Such high-capacity storage is achieved on AMARs and HARPs. The AMAR electronic board features eight channels of 24-bit analog-to-digital conversion and can host up to 16 solid-state memory modules, each of which has a capacity of 128 GB, for a total of 2 TB of on-board memory (JASCO, 2009b). Similar high-capacity data storage on HARPs is achieved using 16 integrated laptop hard drives arranged in a block and addressed sequentially through a single 50-pin bus. The 16-drive block can be easily removed and replaced following instrument recovery (Wiggins & Hildebrand, 2007).

Monitoring high-frequency sounds of some marine mammal species can also be achieved by using triggering algorithms. The PAL (Nystuen, 1998, 2006; Nystuen et al., 2007), the EAR (Lammers et al., 2008), and the DMON (M. Johnson, pers. comm., 25 August 2008) are examples of ARs that include electronics to monitor continuous sound and only save information on sounds that trigger the detection algorithms. For example, the EAR has a signal conditioning module that includes circuitry that monitors the input signals for specific types of acoustic events (Lammers et al., 2008).

Hydrophones—As part of their systems, AR developers include hydrophones that are off-the-shelf, customized by other companies for their specific device, or build their own. For example, GeoSpectrum Technologies (GTI) is a company that designs and manufactures custom acoustic transducers, including directional hydrophones for AMARs (particle velocity sensors; JASCO, 2009b). DASARs use technology developed for DIFAR sonobuoys by Greeneridge Sciences and also include two horizontal, orthogonal directional sensors (particle velocity hydrophones) and one omnidirectional pressure sensor. In order to have information on the DASARs' reference direction, it is necessary to perform acoustic calibration transmissions, which can provide precise bearing data (Greene et al., 2004; Blackwell et al., 2007). This allows the bearing to the sound source to be estimated so that animal sounds can be localized and, in some cases, so that animals can be tracked (Blackwell et al., 2012).

HARP developers designed a low self-noise, high-gain hydrophone that can pre-whiten (adding more gain at higher frequencies where ambient noise levels are lower and sound attenuation is higher) ocean ambient noise across four frequency decades (10 Hz to 100 kHz). This is achieved using two separate stages of signal conditioning, one for a low-frequency band (10 Hz to 2 kHz) and another for a high-frequency band (1 to 100 kHz) (Wiggins & Hildebrand, 2007). These two stages use different transducers—a single, spherical, omnidirectional transducer for the high-frequency stage and six cylindrical transducers connected in series for the low-frequency stage—and provide the ability to record both baleen whale low-frequency and high-frequency sounds produced by odontocetes. The signals from these two stages are pre-amplified and pre-whitened and are then added together via a differential receiver (Wiggins & Hildebrand, 2007).

Some developers adopt standard field practices that include calibration of all hydrophones before deployment or on recovery; others calibrate the entire AR system. Calibration is an important issue and must be addressed for many PAM applications.

Power Supply—ARs operate autonomously and, thus, must be powered internally by a set of batteries. AR developers design their systems aiming for low-power consumption and include user options to use different battery types, sizes, and quantities in their systems depending on the desired capabilities and design. Different batteries are used to power the AR systems reviewed herein (Table 2). Alkaline batteries are cheap and relatively safe to dispose of, but they provide less power and are not ideal for high-drain devices because they cannot deliver power quickly. On the other hand, lithium batteries are more expensive (cost at least twice per Amp-hour compared to alkaline), are relatively more toxic to the environment, and can explode if short-circuited. Still, they last longer than other batteries and are more reliable due to a low rate of shelf discharge (Bluejay, 2009). Nickel-Metal Hydride (NiMH) batteries are rechargeable but less reliable (high shelf-discharge rate and inaccurate voltage readings that can result in sudden discharge) and put out less voltage than alkaline batteries. Lead-acid gel cells are also rechargeable but give off potentially explosive gases and are more expensive than NiMH batteries (Bluejay, 2009).

Package Design and External Configuration, Deployment, and Retrieval Issues

Another consideration with ARs is external configuration (e.g., shape and size of the package). The choice depends on (1) the system capabilities required by a specific application; (2) the environmental conditions and substrate type in the deployment area (e.g., type of ocean bottom, presence of strong currents and surface winds, bathymetry, vessel traffic, bottom fishing activities, etc.); and (3) deployment logistics, which include the type of vessel and hoisting equipment available for deployment and retrieval (e.g., winches, cranes, A-frames, and divers), all of which have an impact on type and configuration of instrument (or vice versa).

Depth Rating—AR housings have depth ratings that specify their maximum deployment depth. Some, like the pop-up, have a depth rating up to 6,000 m but because of limitations related to the release mechanism, the depth rating is often decreased to as shallow as 2,500 m (T. Calupca, pers. comm., 14 January 2009). In shallow deployment cases, the depth rating is environmentally dependent and site specific because it can be reduced even more due to increased noise from high sea states, ocean floor topography, variation in sound speed profile, and natural and anthropogenic sources of noise.

Details of the biology of the species of interest, deployment area, and the scientific question(s) to be asked all dictate the depth necessary for an AR. For example, the acoustic behavior of deep-diving species like beaked whales and elephant seals can only be monitored effectively with ARs that can be deployed to depths below ~1,500 m (Johnson et al., 2006).

Instrument Deployment—ARs can be moored, deployed using only a small anchor (e.g., pop-ups, AQUAclick, and C-POD), or be used as a standalone instrument (e.g., ARPs and HARPs). These configurations can also be modified to address particular characteristics of a deployment area (i.e., depth, currents, bathymetry, etc.). Some locations might have existing infrastructure for ocean instrumentation in the form of large moorings and other ocean-bottom instrument packages that can be used to accommodate fixed ARs. Additionally, existing and planned seafloor ocean observatories are capable of providing power for ARs via a junction box or node and may also provide logistical support in the form of vessels for deployment and retrieval of instruments (e.g., the Station ALOHA Cabled Observatory [ACO], Duennebier et al., 2008; the Victoria Experimental Network Under the Sea (VENUS), Dewey, 2009). The possibility of using existing infrastructures from oil and gas production platforms as moorings or simple anchoring sites is an interesting and possibly cost-effective solution for repeated deployment plans. Additionally, the availability of auxiliary vessels and highly trained deep diving crews at oil and gas production sites can significantly reduce the operational costs of AR deployment, maintenance, and retrieval. The costs/benefits comparison between the use of acoustic releases and having a dive team to recover ARs should be evaluated for each area.

Moorings can either be large with multiple components distributed vertically along a line, wire rope, or chain (e.g., EARS; Newcomb et al., 2009), or be a small, "homemade" anchor attached to a line or chain (e.g., T-POD; Watkins & Colley, 2004). Moorings can have surface expression (attached to buoys visible at the surface) or be completely underwater (subsurface moorings). Each mooring type has different advantages and disadvantages. Attaching ARs to large moorings with surface expressions provides the following advantages:

- Reliability and ease of relocating instruments for retrieval
- Possibility of providing power and data remotely via radio links (Duennebier et al., 2008; Dewey, 2009)

Disadvantages include the following:

- Need for specialized and costly deployment equipment when the size of the mooring is large (large vessels with trained personnel, A-frames, or cranes are required)
- Possibility of buoy being a navigational hazard
- Possibility of damage and destruction of buoys in areas with natural drifting hazards (e.g., ice in polar areas; Greene et al., 2004)
- Higher total equipment weight and size during deployment and retrieval
- Higher visibility to pirates and vandals
- Higher susceptibility to the effects of storms or other episodic weather events

Surface waves and currents introduce considerable drag and tension on the mooring line from bottom to surface. Nevertheless, moorings can be configured with large mooring lines and considerable flotation and ballast to provide protection from fishing operations and heavy weather/currents, ensuring the mooring maintains its position. Additional requirements to keep large moorings in position, such as flotation and ballast, will make them even larger, thus requiring vessels with heavy lifting capabilities. Smaller moorings can be deployed by divers or from a small boat, and the lifting requirements can be minimized by handling individual components (i.e., flotation, data recording electronics, batteries, ballast, and release system) one at a time (Dudzinski et al., 2011).

The increasing need for PAM in shallow water environments, where currents, winds, heavy vessel traffic, and other conflicting activities are a concern, will require more reliable moorings. Conventional buoys and mooring systems can require considerable resources to deploy and recover. Surface buoys may attract undesirable human attention, unintended snagging/recovery, or collateral damage from other marine activities, such as bottom-fishing, especially in coastal areas.

Subsurface moorings can overcome some of these concerns with reduced component size, but they still consist of multiple physical components (e.g., anchor-weight, securing line, release, payload, and buoyancy unit) and are therefore not usually well-suited for deployment from small vessels with limited manpower (Koay et al., 2002). Some subsurface ARs (e.g., pop-ups, AQUAclick, PANDA, and DMON) are easily deployed from a small boat by a few people without specialized lifting or hoisting equipment. Nonetheless, there may be a need to use either a dive search team or special acoustic equipment (e.g., transponders and acoustic release mechanisms) during retrieval operations. In cases in which a surface buoy is not used, there are higher risks of losing the instrument because there is no marker at the surface. Some devices may offer an option to have a SPG locator on the subsurface unit, which can solve this problem at a reasonable cost.

Anchoring or mooring is an important consideration for shallow water deployments. Proper anchoring is crucial to avoid equipment loss. Some AR developers provide extensive advice on anchoring (e.g., Chelonia Limited, 2007, 2012; T-POD and C-POD user guides; Pop-up user's guide; and in-house training), while others provide little to none. Prior knowledge of the physical characteristics of the area for deployment is invaluable when deciding on the type of anchor necessary. The choice of anchor/mooring type and weight depends on anticipated bottom type, depth, and currents expected at a site (Koay et al., 2002). A few concrete blocks may not be adequate for a shallow coastal sandy seabed as this is a dynamic environment and the instrument package might move in relation to tidal currents and waves. Massive concrete anchors, digging metal anchors, or heavy metal anchors are preferable (Chelonia Limited, 2007). Anchoring also depends on the size and weight of the instrument. There is great variation in the dimensions of the instruments inventoried here, from very small and easily handled by one or two people (e.g., OCEANPOD, OCEANBASE, DSG-Ocean, PANDA, pop-up, AQUAclick, DMON, EAR, SM2M, and mini-AMAR) to very large instruments (e.g., ARPs and HARPs) that require lifting equipment.

The risk of loss, especially for fully autonomous systems, is high if unreliable mooring systems are used, especially when using directional particle velocity sensors, in which case the suspension method is extremely important to ensure that currents and mooring noise do not affect the sensor (JASCO, 2009b).

Instrument Retrieval—Selection of the most appropriate method for AR retrieval is based on water depth, strength of tidal currents, and composition of the seabed, as well as on the external configuration of the AR deployed (e.g., size, mooring type, etc.). There are many release systems available (e.g., mechanical or acoustic), some of which can be quite expensive and often unreliable. The relative cost advantage and reliability of other methods of instrument retrieval (e.g., diver retrieval and grappling) should be considered, in particular in shallow water deployments. For example, the DASAR used by Blackwell & Greene (2006) was retrieved by using a double grapnel anchor assembly with 6 m of chain towed perpendicular and across to the line where the DASAR was moored. Chelonia Limited (n.d.b) shows how to use a vertical grapple in detail. When retrieval by grappling or diving is not an option (or becomes difficult due to weather conditions), a backup release system should be implemented to ensure that a malfunction in the primary retrieval method does not translate into instrument and data loss.

An example of a mechanical release mechanism is on the PANDA; this mechanism will keep the instrument attached to the anchor but floating at the surface for retrieval (Fiobuoy® release mechanism; Koay et al., 2001). The PANDA is designed to leave nothing on the seabed after recovery and thus provides a system that is ecologically friendly. Some areas (e.g., Marine Parks and Marine Protected Areas) require special permits to deploy permanent or semipermanent instruments in the ocean or on the sea floor. Many also require that all components of the anchor/mooring are removed from the seabed after recovery ("nothing left behind"). In addition, the PANDA's release is equipped with an internal leak detector that will trigger an immediate emergency-surfacing sequence in case of leak, avoiding serious damage to the payload and data. Whereas this system has a desirable design, its limitation is that it cannot be used in depths over 200 m (Koay et al., 2002).

AR release systems for deep water deployments may include an acoustic release that can trigger a mechanical release mechanism or accelerate the breakage of a corrodible link, or a timed mechanism that can activate the release system at a preset date and time. Pop-ups, ARPs, and HARPs have been retrieved by activation of a burn-wire release mechanism. An acoustic command broadcast from the recovery vessel using an underwater speaker causes the release system to apply a voltage between the burn-wire and a saltwater ground, accelerating corrosion of the wire. The corrodible wire link releases the device from the weight, and it floats to the surface where it can be either seen or found via a self-contained VHF beacon (e.g., included in the pop-up design; Wiggins, 2003; M. Johnson, pers. comm., 25 August 2008;

T. Calupca, pers. comm., 14 January 2009). Two acoustic release systems can be used on the same AR to provide redundancy and increase the likelihood of instrument recovery in the event of failure of one release system (Wiggins & Hildebrand, 2007).

An acoustic release mooring can either disconnect the AR from its ballast weight, allowing the instrument to return to the surface, or it can release a tethered buoy that returns to the surface, allowing the rest of the mooring to be recovered via the tether line. This system has been used on AMARs. JASCO also offers a "nothing left behind" option to deploy/retrieve AMARs that has several advantages—no anchors remain on the bottom, and the AMAR remains anchored to the bottom when the float and release surface (ensuring it does not get lost after the release is triggered). The third anchor line also remains on the bottom and can be used for grappling if necessary (JASCO, 2009b).

Note that the release systems discussed here are not unique to specific ARs. Dudzinski et al. (2011) offer a detailed review of deployment and retrieval options and related issues that may be very useful for users of ARs.

System Customization

AR systems inventoried herein may be modified to increase some capability in detriment of another (see "Tradeoffs" section). An AR capability that is usually easily modified is total power capacity. The total system power capacity (Amp-hours) information is not always available in the specifications because most AR system configurations are flexible, allowing the user to either change the number of batteries (e.g., single- and double-bubble pop-ups) or battery type (e.g., alkaline battery packs or longer-lasting lithium battery packs) to accommodate the requirements of a specific application.

Some instruments inventoried may offer additional flexibility in other aspects of their design and configuration to better address requirements of each user's applications and deployment areas. For example, JASCO (2009b) has developed a re-usable suite of pressure vessels, suspensions, anchoring systems, and recovery systems that can be customized to meet most requirements; therefore, AMARs can be deployed in shallow water using a cement block and be retrieved by a diver, include an acoustic release system for deep water applications, and also have localization capabilities (directional AMAR configuration, including a vertical hydrophone array). Another example is the NOAA/PMAEL AUH that has been modified to withstand extreme conditions (~0° C water and strong currents of the Drake Passage). Dziak et al. (2007) doubled the strength of the mooring line and replaced the standard laptop hard drives with a sealed industrial drive that is rated to -20° C for that application.

The ability to modify or customize a system can be advantageous for the user. Adaptations that have proven reliable in the past should be used if the application so requires, but system modification prior to extensive field use is not recommended as unforeseen problems in system programming and data management could result in data loss. A change in the instrument software to accommodate recording duty cycles or an increase or decrease in the sampling rate can render the system unreliable because of programming errors or limitations of the hardware without sufficient testing. Caution should be used and pilot tests conducted to ensure system reliability after custom changes.

Noise Issues

Flow and strum noise caused by water motion over the hydrophone(s) can be a problem for ARs in some environments. The DASAR overcomes flow noise using a latex "sock" secured over an aluminum cage to shield the hydrophone from water motion (Greeneridge Sciences, n.d.). Other solutions to this problem include surrounding the hydrophone with a perforated PVC tube (e.g., pop-ups). Unwanted environmental noise (e.g., sea-surface noise) can also be reduced by preconditioning signals via band-pass filters (e.g., HARPs and PALs).

In any AR system, the hydrophones should be free of contact with external objects and the sea floor and not shielded with acoustically absorbing or reflecting materials (which would impair sensitivity, especially for high-frequency applications). High-frequency sounds have short wavelengths that could be missed if parts of the hydrophone are covered or shielded by components of the AR. These sound shadows should be avoided by placing the hydrophones away from the bulk of the package.

Self-generated noise is also an important concern. One of the key functional constraints of an autonomous acoustic recording system is electronic self-noise (Wiggins, 2003). Instruments that use spinning hard drives or other moving mechanical parts can generate undesired signals in the recordings that can mask sounds of interest. This can also impair or reduce the effectiveness of automated detection and classification of calls. The configuration used in ARPs and HARPs keeps the hydrophone well away from any electronic noise generated in the instrument itself (approximately 8.5 m away; Wiggins, 2003). This design has solved the issue of noise produced by the hard drives. The use of nonmoving components for electronic data storage (i.e., flash media) is another effective solution (see additional examples in Table 2).

Deployment Configuration of Multiple Autonomous Recorders for Localization, Tracking, and Density Estimation of Marine Mammals

Performing mammal localizations can be achieved by using a widely spaced array of omnidirectional, fixed AR units, but such a protocol requires synchronized timing of all units. It is often difficult to obtain precise timing with autonomous underwater recorders, each with its own clock drifting in time independently (Wiggins & Hildebrand, 2007). AR time-synchronization can be achieved by recording GPS time-linked signals at deployment and recovery to time-align the recorders. This technology is applicable for localizing acoustic sources such as vessels, seismic sources, or marine mammals. The sensors should be spaced appropriately for the desired spatial coverage, signal bandwidths, or time resolution, and the expected signal to noise levels (JASCO, 2009b). Cornell's BRP uses sound-based synchronization of multiple pop-ups and proprietary software alignment to achieve the same goals. Performed at the beginning and end of deployment, synchronization is a normal procedure when using multiple pop-ups in an array. It involves gathering all the units close together, producing a set of sharp tones, and accurately recording the onset times. This simple procedure allows chronological matching of recordings from all units during the entire duration of the deployment.

Directional ARs (e.g., DASAR and AMAR DV) provide the ability to obtain a bearing to detected sounds without using arrays of recorders. By using an array of these sensors spaced hundreds of meters apart, cross-fix bearings, and time-delay-of-arrival, data are collected that can provide localizations for sources that have lower energy levels. A single directional recorder can also be used to track bearings of a source. Using target motion analysis techniques, the bearings can be converted into a localization and tracked over time (JASCO, 2009b). Calibrations with known position sounds can be very important to the success of the triangulation approach to sound-source localization (Greene et al., 2004). The choice also depends on what species are being targeted, but even so, if a single or few species that produce high-frequency clicks are of interest, it may be more cost-efficient to use sound detectors (e.g., AQUAclick, PAL, C-POD, and T-POD) rather than high-frequency continuous recorders (e.g., HARPs). Additionally, if the area of deployment is deep, the depth rating and retrieval system of these instruments may limit the choices available.

Instrument Theft and Vandalism

Theft and vandalism can be a serious risk to AR retrieval in some areas. Example solutions include obtaining cooperation and advice from local fishermen; using a very small marker with minimal surface expression or subsurface moorings; using acoustic transponder releases; using corrodible links that dissolve after a predetermined time in the water and then release a recovery buoy from the bottom; and using divers to deploy and recover the instruments (Chelonia Limited, 2011, 2012). Offering a reward might improve the likelihood of recovering a lost instrument, sometimes even after long periods of time (R. S. Sousa-Lima, personal experience with one pop-up found and returned by a fisherman a year after losing it). The most effective, reliable solution is usually some combination of these options.

System Availability to Users

The pricing and availability of PAM systems inventoried herein varies depending on the type of organization that provides access to the technology. Private companies usually have relatively straightforward lease or purchase options (providing user support through manuals or staff), while developers from academia, research, and government institutions have customized agreements for use, lease, or purchase of their AR systems. Many of these groups also have technical staff to provide additional data processing services. Pricing also varies depending on time demands and on the amount and type of data processing and analyses provided. For example, some groups tailor pricing to adapt to a broad customer audience that varies from small collaborative research efforts (usually long-term, small scale) to oil and gas industry contracts (short-term, rapid turnaround, high demand).

High costs restrict the number of units that can be deployed and thus reduce the system's usefulness as a monitoring tool (Lammers et al., 2008), especially when array configurations are needed to estimate relative numbers and distributions. Some ARs are available for lower costs in order to make them more accessible for applications that require multiple units (e.g., EAR; Lammers et al., 2008). Availability of multiple devices in a timely manner depends mostly on the technology providers, but also on their suppliers. Devices that are requested often must have production capabilities that meet these demands.

Discussion

Considerations regarding the use of ARs should include the frequency band of sounds produced by the species of interest, the areas and scale over which monitoring is intended, background noise levels, and the specific goals of the study or monitoring effort. For example, a study intended to detect the occurrence of animals near an oil and gas platform could use several independent ARs, whereas one intended to localize and track animals using their calls would likely use an array of synchronized ARs with spacing that would allow tracking over ranges of interest.

ARs can be used in every stage of a well-designed study. ARs are extremely valuable for the early stages of acoustic prospecting when information can be gathered *before* E&P activities begin. The timing of changes in relative numbers of animals is important information that can be used to schedule exploratory activities (e.g., seismic studies), as well as to determine the effects of production and transportation activities on animal occurrence and behavior.

The use of ARs is an effective method for acoustically monitoring marine mammals and especially for identifying which species are present in a given area at a given time (Clark & Charif, 1998; Stafford et al., 1999, 2007; Nieukirk et al., 2004; Heimlich et al., 2005; Mellinger et al., 2007b; Širović et al., 2009), locating and tracking individuals (Sousa-Lima & Clark, 2008, 2009), identifying sounds associated with different regions (Stafford et al., 1999, 2001), and determining patterns of distribution and relative abundance (Mellinger et al., 2004a, 2004b). Among the main constraints for analyzing and interpreting acoustic data collected using ARs is the difficulty of associating the number of sounds recorded with the number of animals present; the detection range and location of the sounds; as well as the seasonal, behavioral, and demographic variations in the calling behavior of different species (Clark & Charif, 1998; Mellinger & Barlow, 2003). The extent to which these types of information can be obtained depends on how the study design takes environmental and biological aspects into account and on how AR units are deployed (e.g., the number of units deployed and the geometric spatial arrangement of the ARs).

Fixed PAM, such as ARs, will continue to be one of the most cost-effective ways to remotely monitor marine mammal species and their surroundings and to collect data on how human activities are affecting these dynamic systems. McDonald et al.'s (1995) study which incidentally detected whale calls using OBSs, also recorded noise from seismic air guns and from ship traffic and is a good example of how ARs can be effective for monitoring noise produced by oil and gas E&P activities while also monitoring the occurrence, acoustic behaviors, and movements of animals in the area.

The demand for offshore petroleum and gas will provide many opportunities to study the effects of oil and gas E&P activities on marine mammals. Underwater sounds produced by E&P activities are superimposed onto an already dynamic and complex acoustic marine environment. The world's ocean can be seen as a mosaic of areas with different animal acoustic ecologies and levels of human disturbance. This mosaic of soundscapes provides opportunities to acoustically compare the effects of noise across different areas with different levels of disturbance within a similar habitat (e.g., whale breeding areas in pristine and disturbed areas), and within a particular area across time (e.g., before, during, and after study designs in areas with planned oil and gas E&P activities). Fixed PAM technologies are well-suited for these types of investigations. Using data collected from ARs, statistical models can be derived to explain the effects of many naturally occurring and anthropogenic phenomena (e.g., Sousa-Lima & Clark, 2008).

The Use of Fixed Autonomous Recorders in Marine Mammal Monitoring and Mitigation During Oil and Gas E&P Activities

Seismic Surveys—Some regions in the world that are important for oil and gas exploration are also areas of high marine mammal densities. When baseline data on species occurrence and seasonality exists, this information should guide the choice of fixed AR systems used. When such information is not available, the best approach might be to deploy a variety of AR systems that can cover a broad frequency band to gather information about as many species of marine mammals that might be present as possible ahead of time (ideally commencing as soon as the area becomes of interest to the oil and gas industry and continuing for at least 1 y) to facilitate data collection on the seasonality of species occurrence.

As discussed earlier, a high sample rate equates to increased power supply and storage capacity demands, which tend to increase the cost of a system. More sophisticated and costly AR packages can be used whenever their capabilities, such as continuous recordings at high-sampling rates (e.g., HARPs) or greater longevity, are necessary to target specific locations, species, or both (e.g., for recording beaked whales; Johnston et al., 2008). For greater coverage or for sampling among several locations simultaneously, less expensive equipment can be deployed in a multisensor array (e.g., EARs; Lammers et al., 2008). The bathymetry of the area to be monitored should also be taken into account. Shallow water propagation effects may diminish the area over which sounds can be heard; therefore, more densely populated arrays of sensors should be deployed if localization capabilities are necessary in areas with propagation issues. Very shallow areas can be monitored using AR systems that are deployed on or near the ocean bottom (such as the AQUAclick, pop-ups, and EAR), thus avoiding mooring lines that can be a hazard to the towed seismic array.

The distribution of seismic exploration activities should provide ample opportunity to carry out controlled experiments in collaboration with the oil and gas industry to identify the effects of seismic activities on the observed behavior or distribution of marine mammals. Opportunistic experiments to determine the effect of seismic surveys on marine mammal vocal behavior can also be conducted using ARs while seismic exploration is ongoing (e.g., Nieukirk et al., 2004; Di Iorio & Clark, 2010). Both planned and opportunistic experiments should take into account biological and environmental factors that vary spatially (e.g., bathymetry and water temperature that affect sound speed profiles and marine mammal food resources), which may influence the natural fluctuations in occurrence and vocal activity of marine mammals.

Construction and Installation of Platforms and Seabed Production Units—Activities associated with the construction and installation of platforms and other production units generate underwater noise. Blackwell & Greene (2006) determined the levels, characteristics, and range dependence of underwater and in-air sounds produced by the Northstar oil development, located in nearshore waters of the Alaskan Beaufort Sea. Vessels (i.e., crew boat, tugs, and self-propelled barges) were the main contributors to the underwater sound field and were often detectable as far as 30 km offshore. When vessels were not operating, broadband noise from the Northstar rig reached background levels at a distance of 2 to 4 km from the source. Northstar sound levels showed more variation during construction of the island than during drilling and production.

The typical occurrence of multiple platforms in an oil production area would allow multiple ARs to be mounted on or close to the platforms, providing a cost-effective way to deploy an array of ARs. This could increase the capabilities of the hydrophone system to allow much greater geographic coverage and easy maintenance, but also would allow the possibility of tracking individual animals and groups. To do this, it is necessary to have some knowledge of the sound propagation properties and underwater noise budget of the deployment area so that hydrophones can be deployed in a spatial configuration that allows acoustic coverage of the area of interest and so that sounds from vocalizing individuals can be detected on multiple hydrophones (at least three). Continuous time synchronization of these hydrophones could be achieved very effectively by monitoring the exact locations and times of occurrence of acoustic events that are detected by all hydrophones. These acoustic events need not be application-specific and could be existing transient noises generated by the normal activities of the production platform.

Oil and Gas Transportation—Vessel traffic has been shown to cause disturbances in the behavior of several species of marine mammals, including humpback whales (Sousa-Lima & Clark, 2008, 2009), gray whales (*Eschrichtius robustus*; Bryant et al., 1994), blue and fin whales (McDonald et al., 1995), and belugas (*Delphinapterus leucas*) and narwhals (*Monodon monoceros*) (Finley et al., 1990), to name a few. Additionally, shipping noise (i.e., background noise from shipping vessel traffic) is the most important contributor to the increase in ocean background noise levels over the last decades (McDonald et al., 2006). Vessel transportation of commodities (including oil and gas) is contributing to overall noise pollution in areas far removed from the production activities (McDonald et al., 1995). Fixed PAM using ARs in areas around shipping lanes can be an effective way to monitor how this source of noise is potentially affecting marine mammals by measuring how much of their acoustic habitat is being lost (Clark et al., 2009).

Potential Areas for Further Development

Increased Power Capacity and Low-Power Electronics—Wiggins & Hildebrand (2007) point out that as larger capacity disks become available, longer deployments at higher sampling rates will be possible. This will require additional batteries which, in turn, means additional weight and additional buoyancy to compensate. On the other hand, lower power electronics and faster data transfer rates from a memory buffer to data storage disks (i.e., disks powered for shorter periods) or flash memory cards could provide alternative means for longer deployments with the same or fewer batteries and lighter components. Several developers are planning higher capacity systems.

Advances in consumer digital electronics (e.g., music players, phones, cameras, etc.) have resulted in dramatic improvements in high-capacity solid-state and low-power processer memory. Microprocessors with lower power consumption would allow longer deployment periods and/or higher sampling frequencies. These advancements are going to be extremely important in future AR technologies and will affect all aspects of AR design and configuration. The result will be lower data storage costs, lower power requirements, and faster data-transfer and writing rates. Flash storage media are replacing the energy-intensive, motorized disk drives currently used (e.g., next generation pop-ups; T. Calupca, pers. comm., 14 January 2009).

Higher energy capacity batteries (e.g., lithium chemistry) will likely be used to provide extra power with the same number of batteries. Until these higher power batteries are used in ARs, an alternative approach suggested by Wiggins & Hildebrand (2007) is to house the extra alkaline batteries separately from the housing containing instrument electronics and to jettison the battery pack during instrument recovery. This would result in less required buoyancy and smaller instrument packaging.

The use of solar cells on surface moorings is also a possibility for increasing deployment duration without increasing size. Other capabilities, such as USB interface for data downloading and rapid battery recharging already implemented in some systems (e.g., AQUAclick and AMAR), allow quick download of the collected data without having to open the main housing. This capability optimizes ship time and reduces deployment and retrieval costs significantly (Shariat-Panahi et al., 2008). More efficient ways to accomplish this should be explored.

Information Networks and Integration—Underwater networks of acoustic relays using wireless modems and receivers with networking capabilities (e.g., AquaNetwork and DSPComm), uncabled autonomous near-real-time systems, or acoustic links offer new ways to communicate data in underwater channels. Ocean observatories are profiting from these possibilities for integrating underwater observation systems (Duennebier et al., 2008; Dewey, 2009). Details on these technologies are beyond the scope of this review but are fertile ground for advancements in fixed PAM systems.

Concluding Remarks

The wide range of AR capabilities reviewed herein is the result of different application needs that have dictated the design and configuration of ARs. Original AR applications were not necessarily directed at servicing the oil and gas industry as they were mostly built for achieving specific research objectives and for noncommercial purposes. As the research demand increased, developers expanded AR capabilities to collect acoustic data for longer periods, in more remote areas, and covering as many species as possible (C. W. Clark, pers. comm., 28 November 2009). Monitoring and mitigation requirements from regulatory institutions that the oil and gas industry must adhere to will be better achieved as the existing technology develops.

Details on state-of-the-industry AR technology are inherently outdated since this technology is moving forward at a fast pace. Any information shown herein that appears to be out-of-date is likely related to a lack of response from developers or because of websites that were not updated.

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