Trouble-shooting deployment and recovery options for various stationary passive acoustic monitoring devices in both shallow- and deep-water applications

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Trouble-shooting deployment and recovery options for various stationary passive acoustic monitoring devices in both shallow- and deep-water applications[a)]

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Deployment of any type of measuring device into the ocean, whether to shallow or deeper depths, is accompanied by the hope that this equipment and associated data will be recovered. The ocean is harsh on gear. Salt water corrodes. Currents, tides, surge, storms, and winds collaborate to increase the severity of the conditions that monitoring devices will endure. All ocean-related research has encountered the situations described in this paper. In collating the details of various deployment and recovery scenarios related to stationary passive acoustic monitoring use in the ocean, it is the intent of this paper to share trouble-shooting successes and failures to guide future work with this gear to monitor marine mammal, fish, and ambient (biologic and anthropogenic) sounds in the ocean—in both coastal and open waters. © *2011 Acoustical Society of America*. [DOI: 10.1121/1.3519397]

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I. INTRODUCTION

The ocean is an environment rich with sounds (Scheifele and Darre, 2005). Naturally occurring ambient sounds are generated by wave action, wind across the sea surface, tidal or storm surges, seismic events, and underwater currents, to name just a few sources (Urick, 1983). Aquatic animals are also contributors to the ambient acoustic environment and include a variety of species from crustaceans [e.g., snapping shrimp (family Alpheidae)] to fishes [e.g., drum, croakers (family Sciaenidae)] to marine mammals [e.g., whales, dolphins (family Cetacea)]. Anthropogenic sounds are also becoming an increasing part of the marine soundscape and are generated by a variety of sources, including ship traffic (vessel engines), construction activities, and low-flying aircraft, among other sources. Different devices have been engineered to record underwater sounds to monitor and learn about animals and their acoustic environment.

Passive acoustic monitoring (PAM) offers the opportunity to document acoustic activity from naturally occurring sources, both biologic and physical, and anthropogenic sources in an identified study area with the least amount of direct labor and greatest degree of safety to human observers and underwater organisms. Passive acoustic gear can be deployed for several days to several months with minimum human intervention, except when data are ready to be retrieved and analyzed. PAM provides a valuable tool for documenting baseline ambient noise levels, presence of specific species in a given area of concern, vocal behavior of species in a given study area, species distribution, habitat use, migration or interaction between individuals and groups in an identified geographic area, and as a mitigation tool especially in seismic surveys and anthropogenic noise assessment (Mellinger *et al.*, 2007). A particular advantage over observations or measurements involving human operators/observers is the

[a)]This work was presented at the 5th Animal Sonar Symposium, Kyoto, Japan, 14–18 September 2009.
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possibility to obtain long data series from remote areas and during periods where weather or other conditions makes it unsafe or impossible for observers to operate.

Passive acoustic survey design and equipment are decided upon to fit a particular study or question. Factors important in design include length of the study, intended subject—noise or animal, frequency range of intended sound source, depth at the study site, and whether localization of sound sources is necessary. While acoustic recording equipment can be stationary or mobile, the focus of this paper relates to the subset of PAM devices that are moored or secured in one place. Stationary configurations include standard moorings (via buoy or anchor) or cabled systems. The anchored unit is diver recovered, acoustically triggered to surface, or programmed to return to the surface after a set time. Mellinger *et al*. (2007) provides a thorough, detailed review of PAM devices and protocols. Recording devices are either operated manually or operate autonomously. Autonomous audio recording devices represent the majority of PAM systems and are discussed in this paper. Most autonomous recording devices can record continuously or be set on a fixed duty-cycle, depending on the frequency band of interest to a study and the duration of a particular deployment (i.e., time at sea recording).

As computers become reduced in size, battery power required for operation becomes reduced while memory space increases and autonomous recording systems become more cost-effective, especially for projects of greater duration. Longer deployments yield more continuous data records from areas typically fraught with obstacles, which can encumber boat-based and aerial surveys. With autonomous devices, data collection is not restricted only to weather conditions or daylight hours favorable to a human observer. As a result, more data on the daily and seasonal variability of ambient noise, and the distribution of various biological sources are available to scientists and other interested groups. Similarly, detailed information on habitat use, seasonally and diurnally, can be collected on various animal species that are difficult at best to study visually at offshore sites. Longer projects lend themselves well to the application of autonomous recording protocols because operators are only needed for the deployment and retrieval of instrumentation and subsequent data analyses.

Autonomous PAM units generally require recovery after the allotted deployment period as data are often saved to an internal storage drive and must be extracted prior to analysis. Some PAM systems have been designed for satellite relay of recordings for near-real-time processing making them powerful mitigation tools. One such system—an autonomous, near-real-time buoy system for automatic detection of North Atlantic right whale (*Eubalaena glacialis*) calls—was engineered to constantly monitor the movement of individuals of this species in an area of high ship activity in an attempt to prevent ship strikes. These PAM units were configured in an array, and signals were uploaded via satellite to computers at the Bioacoustics Research Program, Cornell University, where automatic detections of right whale upcalls were verified by Cornell acousticians (Clark, 2007; Spaulding *et al*., 2009; Tremblay *et al*., 2009).

A. Various types of PAM units

Several autonomous PAM devices are currently available that vary in size, shape, configuration, and acoustic specification. All systems have at least one hydrophone and some systems have additional sensors for environmental variables (temperature, current, light, etc.). Many systems record sounds directly to a disk or memory of the unit (or relayed to land via satellite) but other, more specialized systems record only certain characteristics of the sounds. Recordings are either constant or follow a duty-cycle, and the unit is left to run remotely until either the batteries or disk space is exhausted. The choice of model depends upon the study's design or question as each model has different benefits for particular situations. Several of the most commonly used autonomous acoustic recording devices capable of recording cetacean sounds are discussed in the following sections. Although there are other recording devices in use [e.g., high frequency acoustic recording packages (HARPs, Scripps Institute of Oceanography), directional autonomous seafloor acoustic recorder (DASAR, Greeneridge Sciences)], only systems that are further discussed in this paper are mentioned below.

Ecological acoustic recorders (EARs, University of Hawaii) are autonomous recording devices with a programmable maximum sampling rate of 80 kHz and can be set to record on a programmable duty-cycle, depending upon the planned deployment length (Lammers *et al*., 2008). They can store up to 160 Gb of data and, depending on the selected sampling rate and duty-cycle, can record for up to a year. An attribute unique to these devices is automatic detection capability that is triggered by high amplitude sounds, such as ship noise or close-range cetacean sounds. There are two EAR versions—a shallow-water (to depths to 36 m) and a deep-water version (to 1000 m). These units were designed jointly by the Hawaii Institute of Marine Biology, University of Hawaii, and the Pacific Islands Fisheries Science Center of the National Marine Fisheries Service (part of the National Oceanic and Atmospheric Administration). EARs are used worldwide to study and acoustically monitor a variety of ecosystems, ranging from tropical coral reefs to sub-ice arctic waters.

Pop-ups are bottom-mounted, marine autonomous acoustic recording buoys designed and built by the Bioacoustics Research Program at the Cornell Laboratory of Ornithology (Clark and Ellison, 2000; Croll *et al*., 2002; George *et al*., 2004). Pop-up buoys are suitable for deployment in the ocean to depths up to 6000 m. Depending upon study requirements, pop-ups can be set for low or high frequency recording, with a maximum sampling rate of 64 kHz, and can operate on a set schedule or continuously.

The digital spectrogram (DSG) recorder was developed by researchers and engineers at the University of South Florida and Tucker-Davis Technologies (commercially available from Loggerhead Instruments, Inc.). The recorder is compact ($8 \times 4 \times 2$ cm), affording a wide range of possible deployment options. The DSG recorder samples with 16-bit resolution and is capable of streaming data at an 80 kHz sample rate. Sample rates up to 400 kHz are supported with intermittent sampling. Sample rate, duty-cycle, and other recording options can be modified by the user via a graphical user interface. A data reduction method known as “stutter” is also available to the user. This method compresses data by saving only a certain number of amplitude points in a given sample rate (for example, 200 per 4096 points). While this method works well for tonal signals such as whistles, echolocation can be difficult to detect as the temporal patterns of such signals are disrupted. Data are stored on a Secure Digital High-Capacity (SDHC) card up to 32 GB. Power is supplied using rechargeable lithium batteries or standard D-cells. Deployments have taken place in shallow and deep-water environments.

Several types of PAM devices have been developed specifically to monitor small odontocetes, particularly, harbor porpoises (*Phocoena phocoena*). Harbor porpoises use a characteristic narrowband high frequency (NBHF) signal, which is very well suited for automatic detection. The signal is characterized by being short (100–200 μs) and with energy concentrated in a narrow band around 130 kHz (Møhl and Andersen, 1973; Villadsgaard *et al.*, 2007). A NBHF signal is used by the five other members of the porpoise family and six small dolphins in the subfamily Lissodelphininae (Kyhn *et al.*, 2009) and the pygmy sperm whale (*Kogia breviceps*) (Madsen *et al.*, 2005). The narrowband nature of the sounds makes them easily detectable by means of a narrow band-pass filter, often combined with a reference filter centered below 100 kHz. NBHF systems include the T-POD and C-POD (POrpoise Detector) and porpoise-click-logger (PCL, Aquatech Ltd., U.K.).

The T-POD (POrpoise Detector, Chelonia Ltd., U.K.) was developed by Nick Tregenza and has been produced in at least five different versions. It has now been replaced by the C-POD. The fundamental detection algorithm is common across all versions of the T-POD, but hardware and firmware implementation differ. Thus, as a general rule, data collected with different versions cannot be directly compared. T-PODs rely on a single cylindrical hydrophone, two band-pass filters, and a comparator circuit for detection. One filter is termed the target filter (set to 130 kHz for porpoises) and the other the reference filter (set to 90 kHz for porpoises). Clicks are logged whenever the energy in the target filter exceeds the energy in the reference filter by a preset ratio. (See Kyhn *et al.*, 2008, for further discussion of function and settings of T-PODs and off-line analysis by the associated software).

The C-POD (Chelonia Ltd., U.K., also developed by Nick Tregenza) detection algorithms are more versatile than the T-POD, allowing for better detection of dolphins and other cetaceans that do not use the unique NBHF-signal of porpoises. The possibility for detection verification and species classification of similar NBHF signals are also newly afforded. Briefly, the C-POD uses digital waveform characterization (over a frequency band of 20–160 kHz) to select clicks and log the time, center frequency, intensity, envelope, and bandwidth of cetacean clicks and other sounds that have predominantly pure tone properties. Off-line filtering of data via associated software accomplishes potential species discrimination. Data are stored on a removable 4 GB SD card and operation time is up to 5 months, limited by battery life. A large number of C-PODs have been deployed in recent years, in large scale setups as well as in connection with environmental impact assessment (EIA) studies as a tool to study the effects of offshore installations and activities on harbor porpoises in the North and Baltic seas.

B. Paper objectives

The purpose of this paper is to present methods of successful deployment and recovery of several different stationary PAM devices, used to capture biologic and anthropogenic sounds, in both shallow and deep-water environments. Deployment and retrieval of equipment in the ocean is often fraught with unexpected complications related to sea conditions, weather state, tide, surge, and more. Most of the co-authors convened to discuss various PAM methods at the Fifth Animal Sonar Symposium in Kyoto, Japan, in September 2009, with this paper resulting from the discussions. Each of the co-authors has worked with one or more stationary PAM recorders and each has collaborated on compiling the successful trouble-shooting strategies to assure successful deployment and recovery of the devices and the associated data.

II. METHODS

Both shallow-water and deep-water deployment and recovery operations of PAM units are discussed with respect to procedures and protocol.

A. Considerations for deployment in shallow water

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

1. Bottom substrate type

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

2. Water depth and tide

If a surface float is attached to a bottom-mounted PAM unit, then the line connecting the anchor with the surface marker must be significantly longer than water depth at highest tide, to prevent the unit from being lifted off the bottom by current or waves. The depth at which any PAM unit is placed might affect the type and amount of data collected; experience has shown that porpoise detections differ with depth of the data logger (e.g., Kyhn, 2007), likely due to the relatively short distances at which porpoises can be detected, coupled with their very directional sound beam. Also, if a device (e.g., C-POD) is deployed near the water surface, its detector could be saturated by bubble noise from breaking waves, which could result in a prematurely filled memory card. Thus, caution regarding unit placement can effect deployment time and the rate of false detections. However, conditions differ between locations and no general correlation between deployment depth and performance has been found.

3. Currents and weather

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

4. Local fisheries

Any trawling in a deployment area has the potential to lead to conflict or equipment loss. One solution is to identify a deployed PAM system by large markers, equipped with radar reflectors and light, in combination with an announcement of the deployment positions to fishermen working in the area. However, the need to alert fishermen and other ocean users should always be balanced with the potential for vandalism and/or theft of the PAM system by unscrupulous individuals. In addition, surface markers can be compromised or detached by wind, waves, and currents, so relying too heavily on these can lead to problems. As an alternative, identifying natural barriers to fishing (e.g., large outcroppings) and locations that fishermen avoid are other solutions worth considering.

5. Ship traffic

Even if there is no trawling in a deployment area, high levels of both commercial and leisure vessel traffic can put equipment at risk. For PAM systems with a surface expression, the same solutions outlined for potential fishery interaction are recommended. On the other hand, for systems deployed well below the surface, at depths not directly affected by vessel traffic, it is generally true that the less attention is drawn to the instrument, the smaller the likelihood of a negative interaction.

6. Deployment time

Whenever equipment is deployed for periods greater than one week, the potential wear to all components must be considered. Possibility of wear should be considered whenever rope is used; thimbles might be needed to protect connections and for long time deployments, the use of wires or chains should be considered. When deploying in salt water, the risk of galvanic corrosion can be significant and extremely aggressive leading to failure of metal parts within days in extreme situations. In particular for shallow waters, where there is a risk of reducing conditions due to lack of oxygen, all connections (shackles, thimbles, etc.) should be made of high-grade stainless steel. Iron should be galvanized or protected by sacrificial anodes of zinc and always be of oversize dimensions to allow for considerable loss of material due to wear and corrosion. This is particularly important for chains. Other metals should be avoided when possible and if unavoidable, they should be isolated from each other by a non-conducting material to reduce galvanic corrosion.

B. PAM deployment procedures

1. EARs-general

There are approximately 75 EARs deployed worldwide. One of three approaches is typically used for deployment. Shallow EARs (0–36 m) are attached to an anchoring body, such as a concrete block or lead structure, using stainless steel straps. Depending on local current and wave conditions, the anchors weigh between 35 and 100 kg. Two steel roll bars are sometimes built into the concrete block to prevent it from crushing the EAR if it is overturned. The anchor and EAR are lowered to the bottom by either divers using a lift bag or by a line from a vessel. Where diving is not an option, a buoy is sometimes used to mark the location of the EAR, but that is generally avoided to prevent interactions with surface waves and currents.

Deep EARs (>36 m) are deployed using the combination of a sacrificial anchor and one or more acoustic releases. The anchoring body typically weighs 50–100 kg and is made of sand bags, concrete blocks, or iron chain links from a ship's anchor chain. For deployments of less than 300 m, paired AR-60 acoustic releases made by Sub Sea Sonics are generally used. These operate using a burn-wire mechanism. The package is deployed overboard by hand or with the aid of a winch and a releasing mechanism. During recovery, a signal produced by a transducer at the surface triggers the passage of a current through the wire links on the acoustic release, causing them to dissolve. The EAR is made positively buoyant by a syntactic foam collar around it and therefore floats to the surface when released from the anchor. For deployments deeper than 300 m but less than 1000 m, an ORE coastal acoustic release transponder (CART) is used. This is a mechanical acoustic release mechanism that is highly reliable but also more costly.

A third approach to EAR deployments is to couple the unit with an existing mooring. This approach generally involves attaching the EAR in line with the mooring chain of a deep-water surface buoy or as part of a mooring package containing additional oceanographic sensors. Deployments using this approach have experienced mixed success. While some have worked well, others have failed due to either the stress from the vertical motion produced by surface waves or from interactions with both derelict and actively used fishing gear.

2. EAR deployments in Iceland

Two EARs were deployed in Skjálfandi Bay in the northeastern part of Iceland at depths of 60 and 80 m. The intention was to deploy the EARs for 4–5 month intervals for a total deployment time of 2 yr.

Local fishermen were consulted before choosing the exact location and the EARs were deployed at locations where fishing does not occur. Sandbags were used as weights (4×15 kg for each EAR) and two acoustic release units were deployed with each EAR (Fig. 1).

3. Marine autonomous recording units (pop-ups)—Icelandic project

A total of four pop-up units were deployed: Two were deployed in Icelandic waters and two were deployed around the Cape Verde Islands. The two pop-up units in Iceland were deployed south of the village Höfn in the southern part of Iceland on August 22, 2006. Both pop-up units were

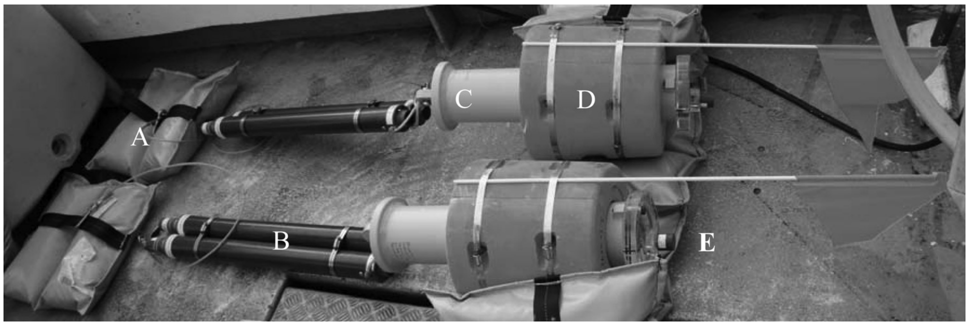

FIG. 1. EARs prepared for deployment. (A) Weight for mooring of the unit, 3—4 sandbags are used for each unit. (B) Two acoustic release units. (C) EAR unit. (D) Syntactic foam float collar (color is often bright orange). (E) Hydrophone.

programmed to start recording in January 2007 for 90 days and to automatically release and resurface ("burn") on July 20, 2007. The two pop-up units around the Cape Verde Islands were deployed on September 25, 2006, southwest of the island Boa Vista and north of the island Maio. These pop-ups were also programmed to start recording in January 2007 for 90 days and the release ("burn") April 20 and 21, 2007. All four pop-ups were deployed using four bags with gravel as weights (30 kg each); tests were made on deck and in water before deployment (Fig. 2). All four pop-ups were deployed at water depth between 210 and 220 m.

4. Pop-up deployment along New Jersey in shallow water

As part of a larger, 2-yr project to assess the baseline ecological use of an area 32 × 97 km along the New Jersey coastline for future proposal wind farm implementation, Geo-Marine Inc. (GMI) deployed between three and six pop-up buoys on a quarterly schedule beginning in March 2008 and finishing in December 2009. Deployment depths ranged from 17.8 to 29.8 m with recording units regularly subjected to storms from the northeast and southeast wind from a westerly direction (from land), and tidal and current surges seasonally. Additionally, this area has an active trawler-based fishing industry and also encompasses an active north/south shipping lane. The shallow depth of the deployment area required a significant increase in anchor weight and design from the typically used rock sacks: 91 or 113 kg steel anchors were used to moor the pop-up above the sea floor for each deployment. A quadruple layer of tubed nylon webbing was used to loop the anchor to the stainless steel shackle on the buoy. The webbing was zip-tied and taped to avoid rubbing on either the anchor eye or the pop-up loop (Fig. 3). Pop-ups were deployed *via* hydraulic winch of a 14.6 m vessel (R/V *Arabella* from Rutgers University Marine Field Station). The units were confirmed to be recording *via* audio cue prior to departure, while on deck on site, at the water surface on site, and lastly on the bottom at each deployment site.

During deployment operations, if the acoustic burn unit was engaged for future recovery, then the winch cables were connected to the anchor loop with the winch holding the anchor weight off the pop-up (Fig. 4). A guide/safety line was employed to keep the pop-up away from the anchor during deployment while at the surface near the vessel's hull. If the acoustic release burn unit was bypassed, then the pop-up and anchor were held at the surface for audio confirmation *via* the pop-up's top stainless loop with the tension from the weight equally distributed to the four "corners" of the pop-up hard hat (Fig. 4). Sea surface conditions encountered

FIG. 2. Pop-up rigged prior to deployment in Icelandic water. A denotes the weight (sand/gravel bag). B is the pop-up. C is the acoustic release unit. D is the rigging used to deploy the pop-up.

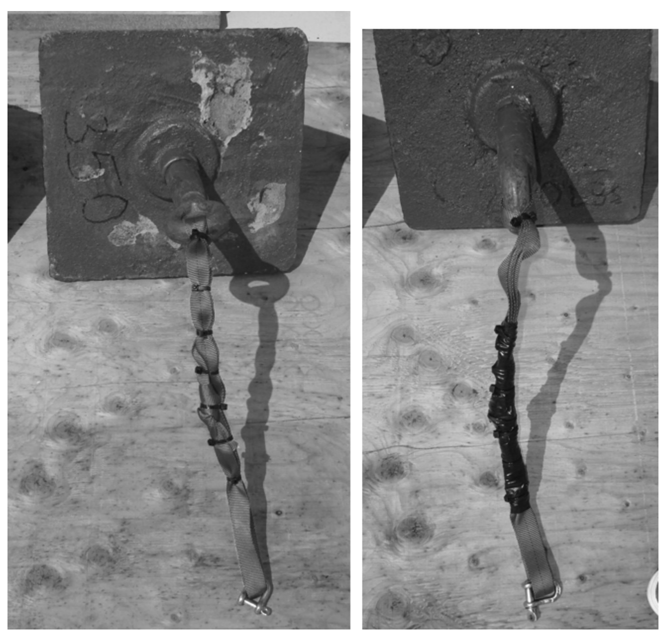

FIG. 3. Anchor rigging used during five deployments during the GMI NJDEP project. The left image shows the webbing prior to tape application; the right image depicts the rigging ready to deploy.

FIG. 4. Deployment of pop-ups during the GMI NJDEP project. The left photograph depicts a pop-up being deployed with the acoustic burn release by-passed. The right photograph presents a unit being deployed with the burn unit engaged (A) and a GPS tracking system (B) attached to the pop-up.

during deployment operations ranged from a Beaufort 1 to a Beaufort 5.

5. POD deployment procedures

National Environmental Research Institute (NERI) has developed a standard method for deployment of T-PODs and other loggers that has proved reliable and successful for long-term deployments in shallow waters. It is a double system with two anchor blocks and two surface markers (Figs. 5 and 6). The main marker buoy is attached by means of a heavy chain to the main anchoring (Fig. 5), which can be either a concrete block or preferably a 50 kg iron ring ("P-ring," Fig. 6). The ring has short wings attached on the outside that bury into the bottom making the ring extremely resistant to pulls parallel to the seabed. A chain is preferred over rope or wire as a tether for two main reasons (1) high resistance to damage caused by collision with propellers, and (2) given that the chain is significantly longer than the water depth, the excess chain will curl up on the seabed and act like a spring that can absorb all up and down movement of the buoy caused by waves and swell, preventing any strain on the anchor system (Fig. 5). Only in very rough water or very strong current will the chain be partly stretched and, even in that situation, will still be able to absorb a large part of the movement. The main buoy is equipped with a yellow cross, radar reflector and sometimes a yellow warning light, as required by naval authorities.

The smaller marker, often just an air-filled float ("Scotchman") is attached with a rope or preferably with a steel reinforced rope (taifun-wire) to the second, smaller anchor. To prevent entanglement of the rope/wire and the anchor and to reduce wear, the last 2 m of wire is replaced with a chain inside heavy plastic tubing. This effectively prevents entanglement or wear related to rubbing of the wire against the anchor block/iron ring. The small anchor is attached to the main anchor by a second rope or taifun-wire, stretched along the bottom. The data logger (T-POD or otherwise) is attached with a carabineer hook to this bottom wire a few meters from the small anchor. The bottom wire must be sufficiently long to allow for the small anchor and the data logger to be retrieved without pulling on the main anchor.

The main anchor is deployed first, together with the main marker. If the main anchor and chain is heavy, this must be done by means of a crane or A-frame. Following this, the small anchor and buoy is deployed, with the data

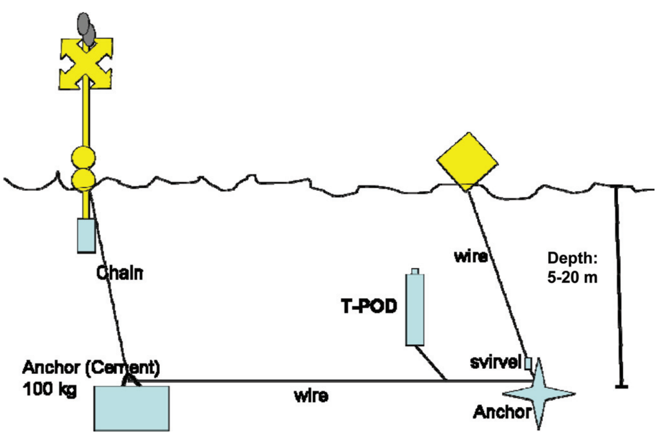

FIG. 5. (Color online) T-POD deployment system for long-term deployments in waters up to 20 m depth. The main anchor and buoy are connected by a heavy iron chain and must be deployed and recovered by a crane. The main buoy is equipped with yellow warning cross, radar reflectors, and light as required by naval authorities. The small anchor and marker ("calf") are connected by a steel reinforced rope (taifun-wire) and can be recovered from a smaller boat by hand or with a small capstan. The two anchors are connected by a taifun-wire onto which the T-POD is attached.

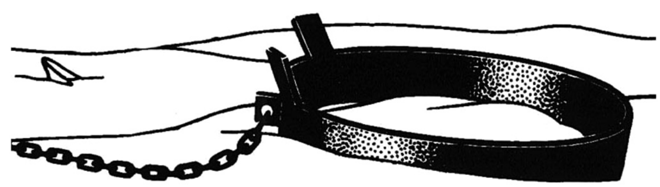

FIG. 6. P-ring used for anchoring for T-POD and C-POD units. The two spikes on the underside of the iron ring prevent the ring from being dragged sideways. Even on hard sand bottoms this anchoring can withstand very high pulls in the horizontal direction. To prevent entanglement, the first 2 m of chain can be covered in plastic tubing.

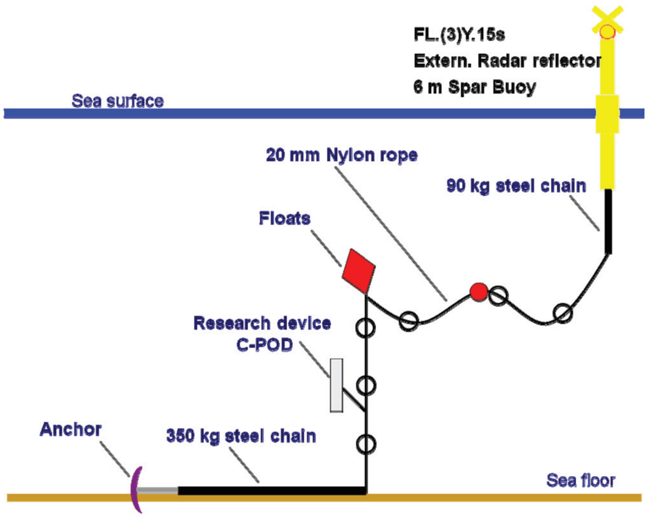

FIG. 7. (Color online) Schematic of deployment arrangement for C-PODs in the North Sea as used by the FTZ Westküste (the system was designed in cooperation with the German Oceanographic Museum and the German Federal Maritime and Hydrographic Agency). The research device (C-POD) is attached to the mooring system by a stainless-steel karabiner allowing for quick and easy exchange of the deployed device for a new one by divers. Black circles indicate heave rings spaced 5.5 m apart along the nylon rope.

logger attached to the bottom wire. The bottom wire must be completely stretched when the small anchor reaches the bottom. Servicing the logger can be done by retrieving the small float and pulling up the small anchor and the logger. This is often possible to do from a much smaller (and hence cheaper) boat than required to deploy and recover the main marker. Furthermore, as the main anchor remains in place, redeployment can take place at the exact same location as recovery (within the uncertainty given by the length of the bottom wire).

A different system for deployment of small cetacean loggers has been designed by the Forschungs- und Technologiezentrum (FTZ) Westküste in cooperation with the German Oceanographic Museum and the German Maritime and Shipping Authority. It consists of a single line instead of the doubled system used by NERI. Anchored with a steel chain of 350 kg, a 20 mm nylon rope is held upright in the water column by floats attached 10 m below the surface; from there the line—in total at least 1.5 times the water depth—is attached to the bottom weight of the single surface marker (6 m spare buoy), which is equipped with a top light, radar reflector and top cross (Fig. 7). The data logger is attached to the lower part of the system at 10 m above the ground. This system is designed to be maintained and the data loggers to be exchanged by divers. However, for retrieval of the complete system, heave rings have been spliced into the rope at 5 m distance.

6. *DSG deployment procedures—West Florida*

The DSG recorders have been deployed in several different configurations. Two major deployments were conducted on the West Florida Shelf in waters from 4 to 100 m depth with the intent of recording sounds from various dolphin species and red grouper (*Epinephelus morio*), among other sound-producing fishes. This area exposes the recorders to a variety of potential abuse from heavy ship traffic, commercial fisheries, a large recreational boating community, and tropical weather systems.

a. Bottom-mounted shallow-water deployment of DSG. A test deployment on the West Florida Shelf in 2008 in 30 m depth was appropriate for a bottom-mounted design (Fig. 8). Protective enclosures were constructed to house the DSG recorders (Fig. 9). These enclosures, 1 × 1 m at the base and a flat-top pyramid shape, were composed of a concrete base and a fiberglass apex and held a waterproof polyvinyl chloride (PVC) housing encapsulating the DSG recorder and battery packs. Stainless steel cables held the fiberglass and concrete components together. The entire recorder assembly weighed approximately 60 kg in air. This design was intended to resist shrimp trawling, which is common in the area. The PVC housings were pressure tested to 100 m. An HTI-96-MIN hydrophone (Biloxi, MS) led from a bulkhead connector on the PVC housing to the top of the fiberglass apex. A sub-surface float was attached to the concrete base with a polypropylene line to aid divers in recorder recovery. Deployments involved manually lowering the unit to the sea floor and capture of exact GPS coordinates.

b. Shallow to deep-water deployment in the mid-water column. A second, larger deployment at 63 stations occurred in 2009 with an alternate deployment design (Fig. 10). PVC housings were pressure tested to 200 m and used to house the DSG recorders and battery packs. To keep the recorders at 10 m or shallower in areas with depths to 100 m, the units were mounted in PVC cages designed to resist impact from shrimp trawls and other fishing gear. The cages were composed of four semi-circular arms, which enclosed one or two centrally mounted recorders. The arms were watertight, providing buoyancy for the recorder, and covered with anti-fouling paint. The cages floating at 10 m were connected with polypropylene rope to the bottom mooring, which consisted of two concrete-filled cinder blocks connected with galvanized chain. A surface polypropylene line with a single sub-surface float and two bio-fouling resistant surface floats was attached to the top of the PVC cage. Lead weights between the sub-surface float and surface floats prevented slack line from trailing at the surface. Additional recorders targeting red grouper, a demersal species, were directly attached to the mooring line near the bottom without a cage. Deployment of the DSG system involved trailing out the floats, the caged recorder and line from the idling vessel, and, once at the desired location, dropping the mooring blocks off the back of the boat.

C. PAM recovery procedures

1. *EAR recovery—general*

Shallow EARs are generally recovered by divers. For long-term studies, a replacement EAR is often carried by the diver and used to replace the recovered EAR *in situ*. Deep EARs are recovered by activating the acoustic release from the recovery vessel using a deck unit with a transducer as described previously. Following release (by either burn wire

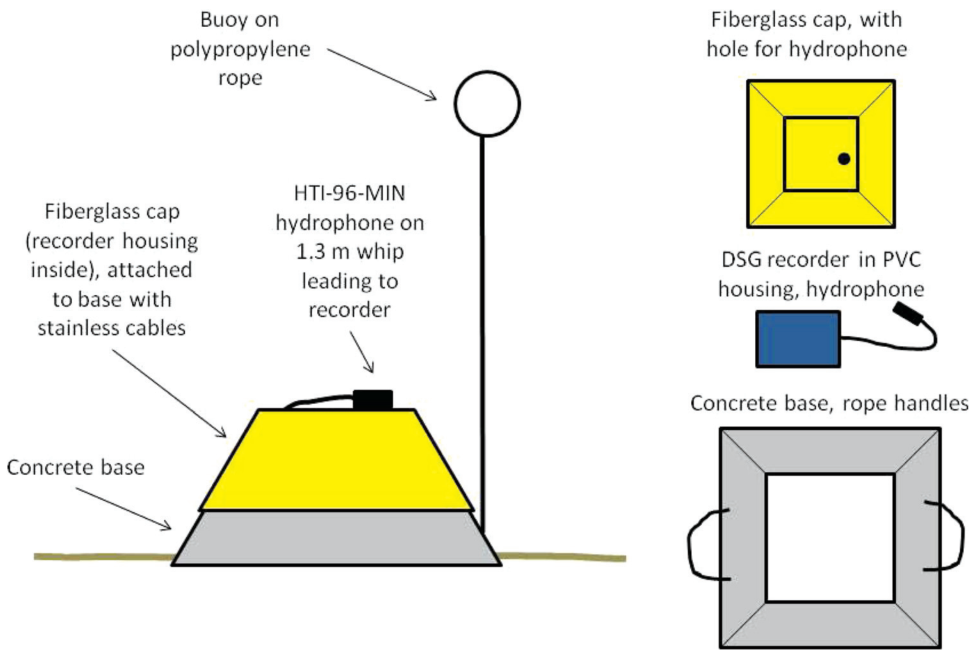

FIG. 8. (Color online) The mooring structure for 2008 deployments of the DSG recorders, with details of the components on the right. DSG recorders and battery packs housed in water tight PVC housings Seacon connector lead to HTI-96-MIN hydrophone on 1.3 m whip; PVC housing held with stainless hose clamps inside fiberglass trawl resistant cap; hydrophone on whip attached to top of cap; cap attached to concrete base with stainless cables; subsurface buoy (~3 m above bottom) aided in diver recovery.

or mechanically), the ranging function of the acoustic release is used to establish whether/when the EAR is on its way to the surface. In addition to the brightly colored foam collar, deep EARs are outfitted with a small flag to aid its visibility at the surface. Needless to say, having good surface conditions (Beaufort sea state <4) and accurate maneuvering of the vessel close to the anticipated surfacing location are very important at this stage. The floating EAR package is brought onto the vessel by a single person lifting it directly from the water.

2. EARs—Iceland

The EARs were deployed for 5–5½ months, and to-date they have been retrieved three times. The EARs were retrieved using a sound-signal emitting interrogator. The retrieval was only performed during good weather conditions—sea state of Beaufort 2 or less and high visibility, since the EARs must be spotted by eyesight on the surface.

During the winter and in cold water, it is to be expected that recovery of PAM units will take more time; it took up to 2 h to retrieve each EAR after sending the first burn audio signal. During summer months, it took approximately 30 min to recover each EAR after emission of the first burn audio signal.

During each recovery, the burn signal was only emitted at short range (153 m). With greater distance, it was more likely that acoustic contact with the unit would be lost. The burn signal was emitted again, as often as possible if contact was lost and continued until the interrogator operated during the entire burn period (i.e., 15 min). The vessel's drift was measured with a GPS and a drifting buoy was deployed before emission of the burn signal. The range between the interrogating hydrophone and the deployed EAR was monitored and kept constant until the unit released.

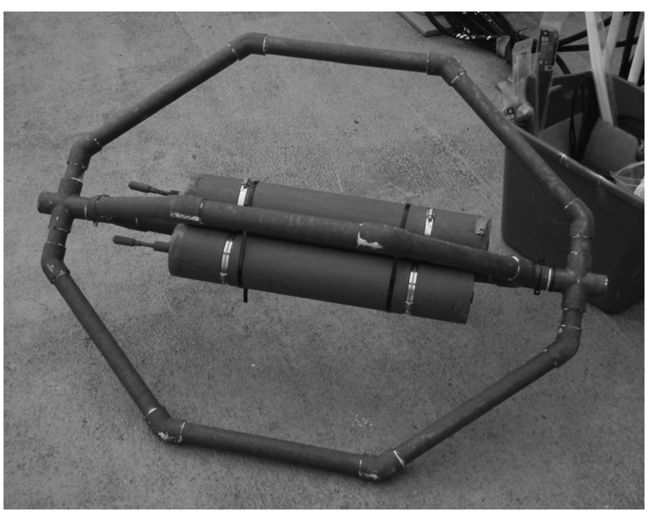

FIG. 9. PVC housings with DSG recorders and battery packs, attached to the center post of a protective PVC cage (pre-deployment). Note that the recorder housings are held to a protective cage with both stainless hose clamps and large tie wraps.

3. Icelandic pop-up recovery—Cape Verde Islands

Retrieval was done from a sailing boat. Three hours prior to the automatic burn time for the first unit, set for April 20, 2007, establishment of communication was attempted at the deployment location. The surrounding location was searched, but no reply was received from the pop-up. After the automatic burn time, a very high frequency (VHF) antenna was employed to listen for the VHF signal to locate the unit while sailing around the area. However, no signals were recieved and the unit was not found at this time. In February 2008, the unit was spotted with a local fisherman using it as a flotation device in his fishing gear. American and local authorities were contacted and a representative from Cornell University retrieved the unit and returned it to the United States.

The recovery vessel was on location 1 h before the automatic burn time for the second Cape Verde unit on April 21, 2007. Communication was established and burn signals were emitted 20 min before the automatic burn time. The unit was

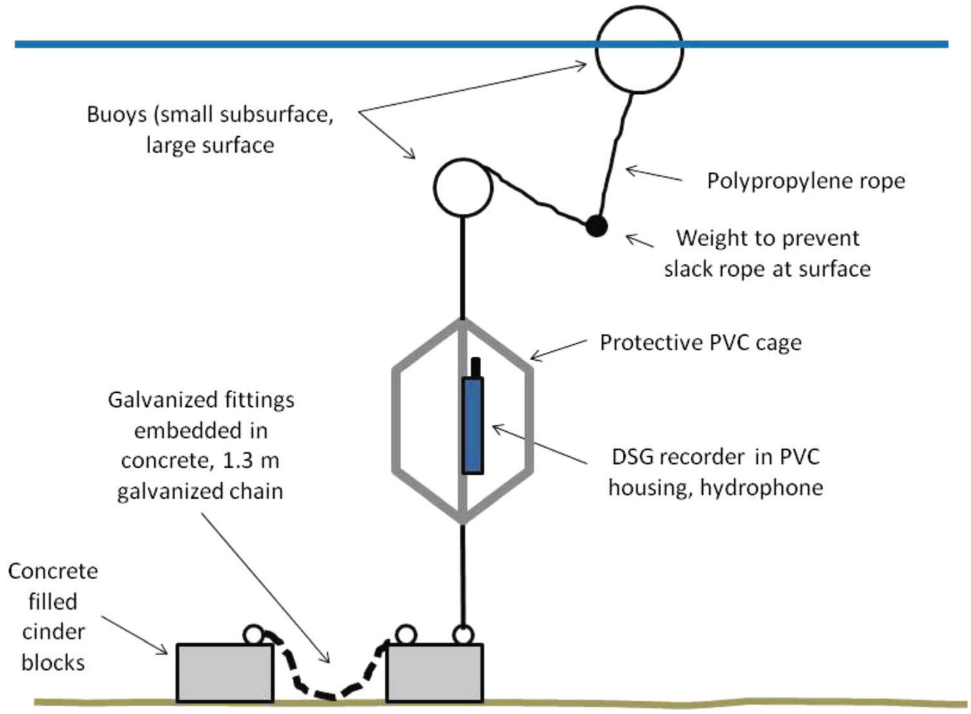

FIG. 10. (Color online) Modified mooring design for the 2009 for the DSG recorder deployments.

sighted at the surface 19 min after the first burn signal had been emitted.

4. Icelandic pop-up recovery—Iceland

One pop-up was trawled by a fishing trawler during winter 2006. The pop-up was driven to Reykjavik and tested in January 2007. Because it was still working, the decision to redeploy it was made. It was deployed by local fishermen in January 2007 at approximately the same location.

On May 20, 2007, the first retrievel atempt of the pop-ups in Icelandic waters was done using an Icelandic rescue boat. Communication was initially established on site with the first unit and burn signals emitted once, but then no contact or communication was established again. The VHF antenna was used to listen for signals from the VHF and the area was searched, but the pop-up was not found. The weather deteriorated with no further retrievel attempt completed.

The second attempt at recovery was on July 20, 2007. An attempt to establish contact at the deployment location of the second unit approximately 1.5 h prior to burn time was unsucessful. At the burn time, the area was searched with a VHF antenna, but no signal was received. Another attempt at recieving a signal from the first unit was unsuccessful. Neither unit was found at this time.

The first unit was never found. The second unit was found on the beach close to Vík in the southern part of Iceland in August 2007.

5. New Jersey pop-up recovery procedures

The same vessel for deployment operations was also used to recover pop-ups on all but one occasion. An audio burn release signal was used when the acoustic burn release was engaged. Once on site, at the deployment GPS coordinates per deployed pop-up, a hello signal and then a burn acoustic signal were played for each individual pop-up. If the hello signal was clearly returned, the acoustic burn was played twice to engage the burn. The delay between the second burn signal and observation of the pop-up at the surface ranged from about 6 min to never (i.e., for lost buoys). Once the unit was sighted at the surface, hydrophone and transducer cables were retrieved while one observer kept an eye on the pop-up. The unit was retrieved *via* a boat hook and secured on deck.

If the pop-up did not respond to a hello signal, the unit also did not respond to a burn audio cue. All units that did not respond acoustically are still lost at sea. A cross pattern search was initiated for all non-responsive buoys with a minimum of 45 min spent on looking for each unit, assuming the weather was cooperative. The deployment GPS coordinates were also traversed with a fishfinder engaged. It was previously determined that the pop-up was visible (newly deployed and with three months of growth affixed to it) on the fishfinder screen. All lost buoys did not appear on the fishfinder. One unit from the second deployment (June 2008) responded acoustically to all audio cues, but did not surface. This unit was diver recovered as it was deployed to 28.7 m. The diver dropped a buoy marker over the GPS coordinates and dove to the unit, arriving within 5 m of the buoy (strobe visible at depth). Two other pop-ups, from the fourth deployment (December 2008), also responded to all audio cues but did not surface. The weather conditions deteriorated severely and precluded our ability to recover them. One unit surfaced two days later and was recovered by a tug boat. The second unit stopped recording 10 days after audio cues and the attempted recovery; however, it was found floating about 7 miles off Virginia Beach, Virginia, on June 7, 2009. Both of these units were retrieved from their rescuers by car. For differing reasons, their acoustic release mechanisms malfunctioned. Three units deployed on the fifth deployment (March

2009) were shackled to their anchors with the burn unit bypassed. One unit broke free during a spring storm with high surge, waves, and tides and was found off Cape May, New Jersey, on June 7, 2009. These units were floating at sea for a variable number of days but were ultimately recovered.

6. POD recovery

Although the double setup used by NERI can be serviced with a small boat, recovery requires a larger ship, mainly due to the use of chains between the main buoy and the anchor. Recovery of the main anchor must be done by means of a crane or a winch with a special capstan suited for chains.

A by-catch issue of an unusual kind became apparent after installing the C-PODs in the southern North Sea. This area is characterized as an industrialized marine area with numerous types of intense anthropogenic use (OSPAR 2009), one of them is fishing. A conflict was identified especially with bottom trawling for flat fish. While this type of fishing is not allowed in the "flounder-box," a protected near shore area for flat fish, the area north of this box faces an even higher fishing pressure. This area is also the planned site for several thousand offshore wind turbines. As a part of the required EIA, the habitat use of harbor porpoises must be investigated prior, during, and after the construction of wind turbines.

Additionally, the fishing vessels equipped with a maximum power of 2000 hp can trawl objects up to several tons of weight without damage. Even though the buoy positions of all C-POD deployments were officially announced and published in an official newsletter by the maritime authority prior to the study, a high percentage of the deployments were trawled-up by fishermen. Most of the buoys, the mooring system (except "useful parts"), and the C-PODs were thrown overboard separately. While some buoys washed up on shore (partially damaged), the remaining parts, including the data bearing C-PODs, sunk to the sea floor and remain lost. Moreover, as the buoys are now drifting uncontrolled through the North Sea, the risk for collision with any type of ship has increased, resulting in considerable damage to the propulsion system in some fishing vessels.

This unexpected loss of deployment systems occurred irrespective of the system design, i.e., the amount of bottom weight, whether chains or "unbreakable" ropes were used. The only exception might be the design used by the Dutch research institute, Institute for Marine Resources and Ecosystem Studies (IMARES), where a particularly heavy setup was used (Scheidat *et al*., 2009) with a bottom weight of 14 tons and large scale buoys as surface markers. However, even with this setup some losses due to collisions with trawlers were encountered.

7. DSG recovery

Recovery of the DSGs in the 2008 bottom-mounted shallow-water deployment was accomplished by divers as only sub-surface buoys were used. Recovery efforts were limited to days in which sea state and visibility were safe and effective for diving. Once the bottom-mounted DSGs were found, divers attached lift bags or rope to the assembly and led them to the recovery vessel. The larger 2009 deployment is still operational; however, recovery operations are ongoing as this manuscript goes to publication. Recovery of the 2009 DSGs is being accomplished with the use of vessel equipment when possible as surface floats were employed: Recorders are ideally recovered by finding the surface floats and hauling the recorder assembly with a commercial fishing pot-hauler. This has proven to be the most efficient and quickest form of recovery. However, if the surface floats are missing, divers are needed to locate the sub-surface float at 5 m, or PVC cage at 10 m. Once located, divers attach polypropylene lines to the cage, which are then hauled up using the pot-hauler. If the site is shallow enough, divers will attach lift bags to the mooring blocks and lead them to the recovery vessel. On occasion, the recovery vessel's echosounder has been used to locate the mid-water DSG with missing surface floats to reduce dive time and thus recovery time. Due to the gentle slope of the West Florida Shelf, the deeper water DSGs (40+ m) are located quite far offshore (85+ km) and therefore require days with fairly calm winds (<10 kts) to reach and work at these sites.

III. RESULTS AND DISCUSSION

When scientists deploy any type of measuring device into the ocean, whether to shallow or deeper depths, it is typically with the hope that this equipment will be recovered. The ocean is harsh on gear; salt water corrodes while animals of varying size claim any surface. Currents, tides, surge, storm seas, and winds collaborate to increase the severity of the conditions that monitoring devices will endure. All coauthors, and numerous un-named colleagues, have encountered the situations described in this paper, and likely many others. In collating the details of various deployment and recovery scenarios related to stationary PAM use in the ocean, it is our intent to share trouble-shooting successes and failures to guide future work with this gear to monitor marine mammal, fish, and ambient (biologic and anthropogenic) sounds in the ocean—both coastal and open waters (Table I).

A. EARs

All EARs, except one from the third deployment, had audio data recorded on their hard drives and each unit functioned as expected despite unit EAR-2 experiencing an unexplained malfunction during the first deployment. The unit stopped recording before filling the hard drive or emptying the batteries. During the second deployment, both recording units functioned as expected. During the third deployment only EAR-1 had audio data recorded; the computer in the EAR-2 unit never began recording. After examination, it was determined that the date and time settings on the computer in EAR-2 had not been saved correctly by the user during programming, resulting in the instrument not turning on when specified.

To avoid unintended problems arising from programming errors, it is important to carefully double check all programming steps and to test all settings on land before deploying the EAR unit. It is also highly recommended that two acoustic release units be used per PAM unit (especially

TABLE I. Summary of deployment and recovery procedure recommendations per PAM unit discussed

Recording unit	Location	Depth (m)	Issues	Recommendations
EAR	Iceland	60–80	Trawl fishing	Run trial setting on land before actual deployment. Consult with local fishermen. Use at least two recording units. Use two acoustic releases. Recover during calm weather, and monitor drift of boat and buoys before release.
Pop-up (Marine autonomous recording unit)	Iceland/Cape Verde Island	210–220	Trawl fishing	Delayed start time is not recommended. Leave long window for recovery in areas of unstable weather.
Pop-up	New Jersey	17.8–29.8	Storms Trawl fishing Active shipping lane Acoustic release mechanism malfunction Shipping traffic	Add GPS tracking system. Use stainless steel cables between the unit and anchor. Directly shackle units to anchor and use diver assisted recovery.
T-POD/C-POD	North Sea and Baltic Sea	Shallow (up to 30 m)	Trawl fishing collisions Wear on all parts By-catch	Increased visibility with stronger lights and an external radar reflector. Open communication with fishermen. Easy recovery with divers in areas without trawling.
DSG	West Florida Shelf	Shallow (to 30 m)	Low visibility for divers Ship traffic Commercial fisheries Tropical weather systems	Use of acoustic "pingers" to reduce time spent to locate equipment.
DSG	West Florida Shelf	Mid-water (out to 100 m)	Loss of surface floats because of vandalism	Use of sub-surface floats only and "pingers," more robust moorings and tether lines.
DSG	West Florida Shelf	Deepsea platform	Size and weight issues	Minor alterations keeping volume in mind.

for deep-water deployments); two releases provide a back up system in case one does not work. If a research team works in an area where weather conditions can be unstable, it is important to choose days when sea conditions are expected to stay relatively constant during the day, preferably with a low sea state and shallow swell since a time window of multiple hours could be needed for recovery operations. Finally, it is recommended that more time be allowed for recovery operations when deploying in cold water, because the time from emission of the first release signal to the time that the PAM unit arrives at the surface can be longer compared to deployments in warmer water.

B. Icelandic/Cape Verde Island pop-ups

Use of a delayed start of recording time is not recommended. In our case, the delayed start time only worked in one out of four units deployed. It is recommended to avoid deployment in areas of heavy fishing traffic, unless coordination with local fishermen is confirmed.

C. New Jersey pop-up study

During the course of the described 2-yr study, six units were not-recovered and are currently considered permanently lost. The primary malfunction was related to the severe environmental conditions prevalent along the New Jersey coast. It is believed that storm surges, strong tides, and high waves likely caused the loss of these units, with trawler-related loss a possibility. However, no evidence currently exists to support trawler-related loss, with the only exception of one pop-up that was recovered one week early and had its double 1/8 in. steel burn unit cables twisted and cut. In response to the significant loss of units (21.4%) and subsequent data, several trouble-shooting solutions were coordinated with representatives from Cornell's Bioacoustics Research Program. Those solutions include (1) addition of an Argos GPS tracking system to two units during the last (6th) deployment for β testing; (2) shifting from the tube-webbing to a 1/4 in. stainless steel cable looped between the pop-up and the anchor (Fig. 11); and (3) directly shackling the units to their anchor (Fig. 4) and thus requiring diver-assisted recovery. All three solutions worked well and all six buoys were recovered from the sixth deployment (August 2009). Additionally, if an automatic burn release is programmed, recovery of the unit has a deadline. Having a pop-up that bypasses the acoustic burn unit and is shackled directly to the anchor allows flexibility in recovery time, should the weather preclude meeting the unit.

D. C-POD units/small odontocete logger

At deployment depths to ~30 m, recovery of C-PODs has proven easy with divers. This cheap and quick method of retrieval facilitates the deployment of a newly-powered C-POD while recovering the existing unit that should contain data. This approach can be executed from a relatively small vessel

FIG. 11. Steel cabling replaced the nylon looped webbing for the GMI NJDEP pop-up deployments. The left image shows five anchors each with steel cable attached. The right image shows the burn unit of one pop-up attached to the steel cable then the anchor.

(reducing costs), as no heavy mooring system needs to be raised to access the device. However, this method is not recommended when there is any sort of ongoing trawling in the area.

In order to overcome the fisheries by-catch interaction issue, two approaches were investigated: (1) The visibility of the buoys at night has been increased by using stronger lights (25 cd., range 3 nm) and by installing an external radar reflector to increase the profile of the unit on a ship's radar. (2) A more important component is to have good, open communication with fishermen in any deployment area. In addition to publishing deployed PAM unit positions in the fishermen's newsletter with a short article explaining the background of the investigation, a direct discussion with representatives of the fishermen's cooperation proved highly productive.

E. T-PODS—*Pros and cons of the NERI setup*

The main strength of the heavy, involved setup for deployment is its reliability, even on hard bottoms during winter storms, and the relative ease with which data loggers can be serviced. The main drawback is that deployment and recovery of the complete setup requires a large ship and crane. The redundancy in the setup, with two anchors and two floats, adds security as the logger can be recovered even if one marker is lost. In cases where both markers are lost, there is a fair chance that both anchors are still in place, together with the connecting wire with the data logger attached. Often, the unit can still be recovered by dredging or a diver.

The relatively long bottom wire can cause problems, if not completely stretched between the anchors. In very shallow water, this can cause the logger to rise to the surface, compromising data collection, and increasing the risk of damage due to ship collision. If the small anchor is too light or the wire too short, then rough weather can dislodge the anchor. Adding a few meters of chain between the small anchor and the surface line can prevent movement caused by waves.

F. DSG recorders

1. Bottom-mounted shallow-water deployment

This deployment method was relatively efficient allowing fast deployment with just two to three people on vessels approximately 12 m in length, even in winds to 20 kts. However, recovery was more difficult and weather dependent due to the diving required. This was the largest disadvantage of field operations resulting in considerably increased time and cost and time lost because of poor weather conditions. Visibility is often low in the West Florida Shelf shallow waters (<2 m), which increases the time necessary for divers to find floats and recorders. Acoustic "pingers" attached to the recorders would reduce the time spent to locate the equipment and are currently being used on two recent deep-water deployments.

Despite the challenges of recovery, 19 out of 23 recorders were recovered (83% recovery rate) in the 2008 deployment. Four recorders were lost; three of which no trace was found, while the concrete base alone was found for one unit. From this information, it is difficult to ascertain the nature of recorder loss; however, shrimp trawling is suspected. It is likely that the two-piece trawl resistant housing was too weak to withstand a direct impact from a shrimp trawl. A more robust design would likely reduce losses in the future; however, for the 19 recovered recorders, all PVC housings remained watertight.

2. Shallow to deep-water deployment in the mid-water column

Deployments were successful with this method and possible for two to three people to manage from 12 m vessels in 15 kn of wind. Deep-water deployments involved considerable lengths of line, which added potential risks to the deployment crew. However, deploying the buoyant components first and the mooring blocks last was considered an essential safety step; potential problems (e.g., tangled line) in deployment could be addressed safely. The 2009 deployment is still operational; however, recorders at 19 stations have been successfully recovered to date. Eight of these were recovered with their surface floats, while the remaining units were recovered with only the sub-surface float or buoyant cage by a diver. Despite use of anti-fouling paint, the cages typically have been encrusted with marine growth and consequently deeper than the original 10 m depth. Recovery at 32 additional stations has been attempted. All of these sites have been dived, as surface floats were not found. While at 10 sites, divers found the moorings with no recorders attached. In all cases, the rope was severed and impact from fishing gear is suspected. No moorings or other gear were found at the other 22 unsuccessful sites; these recorders are considered missing and additional searches are scheduled. Four recorders were found on shore or drifting at the surface (detached from mooring blocks). In these cases, the PVC cages and recorder housings were undamaged but the rope below the cage was severed, suggesting impact from fishing gear. The design with a positively buoyant cage enabled recovery of these impacted units, which would not have occurred with the bottom-mounted design. In addition, the four recorders found on shore illustrated the importance of clearly labeled contact information on the housings.

The loss of surface floats is a concern and appears to be a large problem in certain parts of the study area. It is suspected that these losses are attributed to vandalism by commercial and recreational fishermen and to losses due to impacts from fishing gear. Recent deployments use the original sub-surface float-only design, and Teledyne Benthos acoustic transponders are being tested on two recorders deployed to 100 m depth. Low cost acoustic releases are also being considered; however, designing them to withstand biofouling and potential impact with a shrimp trawl is proving to be a considerable task.

IV. SUMMARY

A summary of all recommendations per PAM unit discussed for recovery and deployment procedures is provided in Table I. The literature is void of details related to failed deployment/recovery attempts since typically only successful recoveries result in viable data for processing and analysis. It is the intent of this paper to provide a non-exhaustive list of options related to troubleshooting in situations when deployment and recovery of these acoustic recording devices has been difficult at best while in the field under varying conditions from good to severe.

V. ACKNOWLEDGMENTS

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