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Review

Comparing methods suitable for monitoring marine mammals in low visibility conditions during seismic surveys

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A B S T R A C T

Loud sound emitted during offshore industrial activities can impact marine mammals. Regulations typically prescribe marine mammal monitoring before and/or during these activities to implement mitigation measures that minimise potential acoustic impacts. Using seismic surveys under low visibility conditions as a case study, we review which monitoring methods are suitable and compare their relative strengths and weaknesses. Passive acoustic monitoring has been implemented as either a complementary or alternative method to visual monitoring in low visibility conditions. Other methods such as RADAR, active sonar and thermal infrared have also been tested, but are rarely recommended by regulatory bodies. The efficiency of the monitoring method(s) will depend on the animal behaviour and environmental conditions, however, using a combination of complementary systems generally improves the overall detection performance. We recommend that the performance of monitoring systems, over a range of conditions, is explored in a modelling framework for a variety of species.

1. Introduction

Anthropogenic sound from shipping, pile driving, the use of explosives, high intensity active sonar operations, seismic surveying and many other activities can mask marine mammal communication sounds, cause changes in the behaviour of these animals, exclude them from important habitats and, in extreme cases, induce auditory injury or death (Erbe, 2002; Gordon et al., 2003; Ketten, 1995; Pirotta et al., 2014; Southall et al., 2007). To reduce the risk of potential impacts, those carrying out industrial projects and naval operations offshore are often required to monitor their operational area for the presence of marine mammals, so that mitigation actions can be taken (e.g. ACCOBAMS Scientific Committee, 2004; IAGC, 2011; JNCC, 2010a, 2010b, 2010c, 2017; Martin et al., 2014; Nowacek and Southall, 2016; Weir and Dolman, 2007). Traditionally, this kind of monitoring involves trained marine mammal observers (MMOs) scanning the sea surface for marine mammals. Visual methods are, however, restricted to daylight hours and relatively good weather conditions. Visual detection is often subjective and happens in an instant, so it is difficult or impossible to confirm or review a detection at a later stage. The effectiveness with which an MMO can visually detect an animal is reduced by weather conditions such as fog, rain, high sea state, sun glare or the lack of light (e.g. Clarke, 1982; Harwood and Joynt, 2009; Palka, 1996; Parente and de Araujo, 2011). Visual detection at night without the aid of additional equipment is impossible. Animal behaviour, such as diving and an undemonstrative presence at the sea surface, can also reduce detection probability.

In recent years, there has been an increased interest in using other

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technologies to overcome the most obvious limitations of visual monitoring. In particular, the use of passive acoustic monitoring (PAM) during monitoring for mitigation purposes has increased, with some national guidelines encouraging its use and industry efforts focusing on improving existing PAM capabilities. Additional promising approaches that could potentially enhance the detection of marine mammals in low visibility conditions include active acoustic monitoring (AAM), thermal imaging (thermal IR) and radio detection and ranging (RADAR).

Passive acoustic monitoring detects an animal's vocalisations using hydrophones (underwater microphones). Active acoustic monitoring is a method where sound pulses are emitted into the water and acoustic reflections from an animal are received by hydrophones. Thermal IR uses an electro-optical imaging sensor to detect temperature differences between the body or the exhalation of the warm blooded marine mammal and that of the surrounding environment. In RADAR, radio or micro-waves are emitted into the air and echoes from the animal's body, its exhalation, or from disturbance on the sea surface are picked up by an array of receivers. Systems using these modalities usually incorporate software detection and/or visualisation tools, usually supervised by a trained human operator who makes the final judgement on animal detection. All of the methods outlined above can be used for marine mammal detection and have the potential to complement traditional visual monitoring methods. Each method has its strengths and weaknesses, and may be more or less suitable for particular scenarios depending on the species monitored and the environmental conditions in which the monitoring takes place. For example, as with visual monitoring, IR and RADAR techniques have the weakness that they cannot detect submerged animals and may have reduced effectiveness in high sea states, whereas PAM has the weakness that it cannot detect silent animals and may miss animals whose vocalisations are highly directional.

The purpose of this review is to reveal each method's strengths and weaknesses from the perspective of monitoring for mitigation, and to list examples of systems which are currently available. We highlight the factors that need to be considered in order to make well informed decisions on the monitoring method, or combination of methods, to apply and the specific systems to use. We discuss the conditions that are favourable or unfavourable for each method and the strengths and weaknesses of each method in terms of both extrinsic and intrinsic factors:

- **Extrinsic factors** are those factors that cannot be influenced by the monitoring team (e.g. sea state, light conditions, animal behaviour, animal size, etc.).
- **Intrinsic factors** are those properties that can realistically be influenced by the monitoring team (e.g. quality and sophistication of the instruments and associated software, method of deployment, etc.).

In this review we focus on evaluating the monitoring methods when applied to marine mammal monitoring for mitigation purposes on a seismic survey vessel, assuming that monitoring systems will be installed on the main survey vessel or on non-specialised ancillary vessels, which is standard practice. This kind of monitoring is generally conducted in the course of seismic surveys. During seismic surveys, acoustic pulses are generated by the seismic sound source and transmitted through the water column into the sea bed (OGP and IAGC, 2011). Some of the transmitted sound energy is reflected by rock strata and received on hydrophones distributed in very large arrays of sensors in long survey streamers, towed by and behind the survey vessel. Acoustic data from thousands of sensors are processed on board and can be viewed as maps showing the structure and nature of the layers in the surveyed area.

Table 1 provides a summary of systems that are available and suitable for such monitoring based on a questionnaire survey of developers, suppliers and users of such monitoring techniques carried out in 2015, supplemented with publicly available information, the practical experience of the authors and contributions from an advisory panel (see Verfuss et al., 2016 for further information).

To understand which of the monitoring methods and systems may be useful for low visibility monitoring conditions, we first evaluate the requirements for effective monitoring for mitigation during seismic surveys and discuss how monitoring effectiveness can be quantified. We then present the results of our analysis, revealing which intrinsic factors (technical or operational parameters) should be addressed to achieve a high detection performance across a wide range of species and how extrinsic factors (animal behaviour and environmental conditions) influence monitoring effectiveness.

An evaluation of the specific systems reviewed highlights their detection, classification and localisation capabilities, and provides ball park figures on the system costs, their commercial availability and installation requirements.

The review concludes by making recommendations for research to assess and improve the effectiveness of low visibility monitoring technologies.

2. Method description and system overview

Each of the methods described is able to detect and classify cues from marine mammals. This section summarises the principle of operation for each method and synthesises the systems listed in Table 1. For definitions of the technical terms and abbreviations used in this review please see Table 2.

2.1. PAM

Marine mammal monitoring with PAM depends on the animal emitting sounds that can serve as cues for detection. Marine mammals produce sound to communicate with conspecifics (Janik and Sayigh, 2013; Madsen et al., 2002; Schulz et al., 2008), for orientation (Payne and Webb, 1971; Verfuss et al., 2005), to locate and capture prey (Au et al., 2004; Madsen et al., 2005; Verfuss et al., 2009), mate selection and social interactions (Janik, 2009; Quick and Janik, 2012; Smith et al., 2008). Marine mammal vocalisations are often characteristic and loud, providing a suite of acoustic cues that can be used to detect and localise marine mammals.

The PAM systems used for monitoring for mitigation purposes during seismic surveys, and listed in Table 1, are of two distinct types: "ancillary" and "integrated" systems. Ancillary systems involve deploying one, or more, dedicated marine mammal PAM hydrophone arrays (streamers) from either the seismic survey vessel or, more rarely, from some other vessel already operating on site (e.g. a guard vessel). Hydrophones are monitored aurally by human observers and/or using acoustic analysis software, such as the open source PAMGuard software (Gillespie et al., 2008; www.pamguard.org), to detect, classify and localise marine mammal vocalisations in real-time. PAM systems of this type have been used for monitoring during seismic operation since the late-1990s. Ancillary towed hydrophone systems are provided by several companies (Table 1), but share several common features. They typically consist of several hydrophones in a terminal array section towed on between 100 and 400 m of strengthened cable. Hydrophones are typically grouped in matched pairs covering different frequency ranges. A deck lead carries signals from the hydrophone termination on the aft deck of the tow vessel to the instrument room where additional hardware providing signal conditioning (filtering and amplification) and digitisation are housed, along with analysis computers (typically high end laptop PCs). One company (Seiche Ltd.) also offers short PAM hydrophone arrays deployed via the seismic source array. This configuration is intended to avoid some of the entanglement risks associated with streaming cables from the aft deck. The most complicated, and arguably the most capable, hydrophone streamer system for which we were provided information on was the "Delphinus" array being