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A field comparison of marine mammal detections via visual, acoustic, and infrared (IR) imaging methods offshore Atlantic Canada

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ABSTRACT

Impulsive sounds generated during seismic surveys have elicited behavioral responses in marine mammals and could cause hearing impairment or injury. Mitigating exposure to seismic sound often relies on real-time marine mammal detection. Detection performance is influenced by detection method, environmental conditions, and observer experience. We conducted a field comparison of real-time detections made by marine mammal observers (MMOs), a rotating infrared (IR) camera, and via passive acoustic monitoring (PAM). Data were collected from a 38 m research vessel offshore Atlantic Canada. Our results indicate that overall detection rates increase when complementary methods are used. MMOs and PAM are likely the most effective combination during high seas and precipitation. PAM and IR can be used in darkness. In good visibility, MMOs with IR or PAM should increase detections. Our results illustrate the importance of addressing false positive IR detections, matching system capabilities to sea conditions/species of interest, and employing experienced observers.

1. Introduction

1.1. Seismic surveys and marine mammals

The ability to detect marine mammals at sea underlies much of the research conducted on wild populations, and in particular efforts to monitor and mitigate potential effects of human activities on these species. Marine seismic surveys are a major contributor to ocean sound (Haver et al., 2017; Klinck et al., 2012a; Miksis-Olds and Nichols, 2016). During a typical marine seismic survey, acoustic energy is generated by a high-energy sound source positioned near the ocean surface and projected downward through the water column to map the geology underlying the seafloor. The sound source, typically an airgun array (i.e., multiple compressed air sources), is towed behind a survey vessel following predetermined survey lines (Caldwell and Dragoset, 2000; Gisiner, 2016). The dominant airgun energy is produced at relatively low frequencies (< 100 Hz; Caldwell and Dragoset, 2000; Tolstoy et al., 2004) that overlap with those used by large baleen whales (e.g., Nieukirk et al., 2004; Richardson et al., 1995). The high-frequency component of the airgun energy is relatively lower in overall energy, and overlaps with the frequency bands used by many species of toothed whales and small baleen whales (10–150 kHz; e.g., Clarke et al., 2019; Richardson et al., 1995). Impulsive sounds generated during seismic surveys have been documented to elicit behavioral responses in many species of marine mammals, and physiological responses to the types of sounds generated during seismic surveys have been shown in other species (Blackwell et al., 2015; Erbe et al., 2018; Gordon et al., 2003; Nowacek et al., 2015; Richardson et al., 1995; Romano et al., 2004; Southall et al., 2007, 2019; Stone, 2015a).

1.2. Mitigation of potential impacts of seismic surveys on marine mammals

Regulations and guidelines have been implemented in many countries with the goal of avoiding or reducing the negative effects of seismic surveys on marine life (Compton et al., 2008; Reyes Reyes et al., 2016; Todd et al., 2015; Weir and Dolman, 2007). Mitigation actions

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are often designed to minimize the probability of marine mammals being exposed to sounds loud enough to cause hearing impairment, and are often triggered when marine mammals are observed entering, or about to enter, a safety zone based on horizontal distance from the sound source. In some countries, mitigation actions are employed for either all marine mammal or all cetacean species (Compton et al., 2008; Weir and Dolman, 2007). In other countries, specific mitigation actions are employed only for certain species or species groups. For example, in Canada, shut-downs of the airgun array are typically required only when threatened or endangered species are observed in, or about to enter, the safety zone (DFO, 2008); in New Zealand, additional mitigation measures are required for listed “Species of Concern” (DOC, 2013); and in Latin America, “higher mitigation standards for certain species” have been proposed (Acosta et al., 2017). Vital elements of effective mitigation therefore include the ability to reliably detect and localize marine mammals in a timely manner, and in some instances, to identify marine mammals to species or other taxonomic rank.

1.3. Methods used to detect marine mammals

Visual observation by human observers is the most common method used to detect marine mammals for seismic survey mitigation purposes. Marine mammal observers (MMOs) typically scan the ocean's surface in a systematic fashion to look for sighting cues, which can include respirations (i.e., “blows”), body parts such as dorsal fins and flukes, presence of seabirds, splashes, and “footprints” (i.e., disturbances left on the surface by marine mammals as they submerge). Visual watches can be conducted with the naked eye, assisted with binoculars, or typically both. Relative to other mitigation methods, MMOs are logistically easy to deploy on vessels in many situations.

The ability to detect and identify marine mammals is influenced by MMO experience level. When compared to experienced MMOs, inexperienced MMOs were found to detect fewer animals (Barlow et al., 2006; Stone, 2015b; Wright et al., 2016), were less likely to classify a detected marine mammal to species level (Barlow et al., 2006), and made detections at shorter distances from the vessel (Stone, 2015b).

The effectiveness of MMOs in detecting marine mammals is reduced when vessel structures obstruct an MMO's view around the vessel, MMOs are looking in another direction when a cue is produced, and when MMOs are fatigued. As well, the ability to visually detect marine mammals is negatively affected by low visibility conditions including glare, fog, rain, high seas, and swell; and is near impossible in the dark (Todd et al., 2015; Verfuss et al., 2018). Therefore, it is often recommended that other detection methods, including passive acoustic monitoring (PAM) and infrared (IR) imaging systems, be used to complement visual observations in order to increase detection rates for marine mammals (Compton et al., 2008; DFO, 2015; Verfuss et al., 2018).

The use of **PAM** is frequently encouraged in mitigation guidelines, and in some cases is a requirement, to complement visual monitoring for marine mammals during seismic surveys, especially at night (summarized in Compton et al., 2008). Towed hydrophone arrays (THA) are a type of PAM system used almost exclusively for monitoring purposes during seismic surveys. Guidelines for some countries explicitly require the use of THAs and specify minimum requirements for the hardware and software components for THA systems (e.g., New Zealand: DOC, 2013; USA: NMFS, 2018). In countries where specific guidance on the type of PAM system is not provided, e.g., Canada (DFO, 2008) and the UK (JNCC, 2017), THA are usually employed (e.g., RPS Energy Canada, 2014; Stone, 2015b).

For PAM to be effective, marine mammals must vocalize relatively frequently during monitoring periods, and vocalizations must be detectable. The effectiveness of PAM in detecting marine mammal vocalizations is not negatively affected by fog or darkness, as with visual methods, but may be somewhat lessened during rainfall or high sea states due to an associated increase in background noise. Depending on equipment configuration and sound produced by the survey vessel and airguns, THA may not be able to detect marine mammal vocalizations, and in particular, the low-frequency vocalizations of some baleen whales. This limitation is explicitly recognized in some mitigation guidelines (e.g., JNCC, 2017; NMFS, 2018).

Infrared (IR) imaging for the detection of marine mammals exploits the radiance difference between a marine mammal cue (e.g., body or blow) at or above the water's surface and the ocean background. Long-wave IR (LWIR; 8–12 μm wavelength) cameras have primarily been used to detect large marine mammals including minke (*Balaenoptera acutorostrata*), fin (*B. physalus*), blue (*B. musculus*), humpback (*Megaptera novaeangliae*), gray (*Eschrichtius robustus*), and sperm (*Physeter macrocephalus*) whales (Cuyler et al., 1992; Guazzo et al., 2019; Horton et al., 2017; Perryman et al., 1999; Zitterbart et al., 2013). Dolphins and pilot whales (*Globicephala* sp.) have also been detected with some systems (e.g., Baldacci et al., 2005). IR imaging systems used to detect marine mammals range in sophistication from IR-capable binoculars and single fixed cameras to a rotating line scanner used to automatically detect whales around-the-clock and with a 360° field of view (Baldacci et al., 2005; Verfuss et al., 2018: Zitterbart et al., 2013). Regardless of the sophistication of the system, all IR imaging systems require stabilization (electronically and/or mechanically via a gimbal).

IR detections of marine mammals are possible during periods of darkness (Guazzo et al., 2019; Perryman et al., 1999; Schoonmaker et al., 2008; Zitterbart et al., 2013) and moderately high sea states. Zitterbart et al. (2013, 2020) report making detections of large whales in Beaufort wind force 4+. The potential for using IR imaging to detect marine mammals in foggy conditions is limited (Verfuss et al., 2018). LWIR transmission loss increases with increasing relative humidity (Winchester Jr. and Gimmestad, 1982), and as a result, LWIR detection range has been demonstrated to decrease with increasing fog (Beier and Gemperlein, 2004). Accordingly, IR detections of marine mammals during foggy conditions are few (Zitterbart et al., 2020). Although the most obvious potential benefit of IR imaging is detecting marine mammals in darkness, IR systems may also assist MMOs that are fatigued or looking in a different direction.

1.4. Motivation and goals of the study

Advances in technology have made it possible for marine seismic surveys to be conducted in increasingly harsh ocean conditions, thereby allowing seismic surveys to be conducted in previously un-surveyed and remote ocean areas and over a greater portion of the year than was previously possible (e.g., Durham, 2012; NMFS, 2012). This increased survey effort has led to growing concerns about the effects on marine life in these regions (Kark et al., 2015; Kyhn et al., 2019; Nowacek, 2013;Nowacek et al., 2015), and about the mitigation procedures' performance under these harsher environmental conditions.

Given the current and likely future extent of marine seismic survey activity, in combination with the potential to negatively affect marine mammals, we had two goals for this research. First, we wanted to improve our understanding of how real-time marine mammal detection methods employed at sea compare and complement each other. Second, we wanted to better understand the relationship between MMO and PAM operator experience level and the ability to effectively detect and classify marine mammals. We made simultaneous and independent observations of marine mammals via visual monitoring, PAM, and IR imaging methods. We compared detections and classifications of marine mammals across these methods and suggest how these methods could complement each other to increase marine mammal detections during seismic surveys.

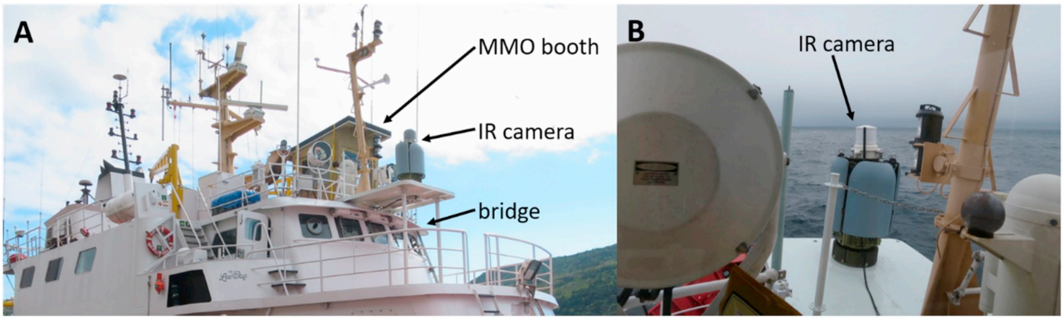

Fig. 1. The RV *Leeway Odyssey* after installation of the marine mammal observer (MMO) booth on the roof of the bridge and the IR camera (A); a gimbal is necessary to stabilize the IR camera at sea (B).

2. Methods

2.1. Survey details

We chartered the RV *Leeway Odyssey* (Fig. 1A), a 38 m aluminum-hulled oceanographic research vessel, for the survey. The *Leeway Odyssey* is powered by two 125 kW CAT diesel generators with a twin-shaft fixed-pitch propulsion system. The survey was conducted offshore of Nova Scotia and Newfoundland, Canada; the vessel departed Halifax on 30 July and returned on 23 August 2017. The tracklines were modified in response to changing sea conditions such that the vessel heading was often matched to the wave direction instead of following predetermined survey lines (Fig. 2). During data collection, vessel speed was maintained as close to 5 kn as feasible to mimic typical seismic survey operation speeds.

2.2. Visual observations

Visual observations were made by one of three types of MMOs: experienced, inexperienced, and assisted. Experienced MMOs (eMMO) were biologists with 15+ years of relevant work experience. All eMMOs had previously surveyed marine mammals from shore, vessel, and aerial platforms including vessel-based surveys offshore Atlantic Canada. Four eMMOs were present during the survey.

One inexperienced MMO (iMMO) was used in this study. The iMMO was enrolled in a marine biology undergraduate program, was familiar with marine mammals, but had very limited at-sea experience. The iMMO had never been formally trained or collected data using a protocol similar to that employed by MMOs as part of a seismic monitoring and mitigation program. The iMMO received a day of technical training immediately prior to vessel departure. Training topics included species descriptions and field identification tips for local marine mammals, survey methodology, and data recording protocols. The importance of classifying marine mammals to only the most specific taxonomic rank in which the iMMO was confident was emphasized. The iMMO was mentored by an eMMO for the first day of data collection on the vessel to ensure that the data collection and recording protocols were understood.

The assisted MMOs (aMMO) were experienced MMOs provided with automatic detection alerts from the IR system. Alerts were relayed directly to the aMMO, i.e., not verified by a human to remove false positives. The aMMO wore a bluetooth headset over which a "beep" was sounded in real-time to alert him or her to a detection. The aMMO could choose to ignore the alert (e.g., if already engaged in making a visual sighting), or view a six second video clip of the automatic detection (Fig. 3) on the data collection tablet. Distance and bearing to the automatic detection were supplied to the aMMO along with the video clip.

Visual observations were made concurrently from two locations: from the bridge and from a booth on the roof of the bridge (Fig. 1A). The approximate viewing heights were 5.4 m and 7.7 m above the water's surface for the bridge and booth, respectively. Both locations had slightly obstructed views looking forward and to the sides of the vessel, but no view of the water directly behind the vessel. The MMO on the bridge was instructed to remain inside the bridge in order to maintain independence from the MMO on the roof. Observations were made from both locations during all daylight hours except when environmental conditions made it unsafe for an MMO to ascend to the rooftop observation booth. Each day, individual MMOs made observations from both bridge and roof observation positions such that the different types of observation effort (i.e., eMMO, iMMO, and aMMO) were roughly evenly distributed between the two positions. Maximum observation shift length was 3 h.

MMOs scanned the water's surface to the front and sides of the vessel for marine mammals with the naked eye or using Fujinon 7 × 50 mm reticle binoculars. MMOs recorded bearing and distance (estimated using reticles) for each sighting using *Mysticetus* software (by Mysticetus LLC, mysticetus.com). *Mysticetus* simultaneously recorded GPS data, automatically logged the time and vessel position, and instantaneously calculated the geographic location of each sighting. Calculations for sightings made from the bridge and roof accounted for the different viewing heights. MMOs classified marine mammals to the most specific taxonomic rank in which they were confident. The following additional information was collected for each sighting: cue, behavior, direction and speed of travel, and group size. Individuals were considered to belong to a group if the approximate distance between individuals was within two body lengths for baleen whales, 10 m for dolphins and pilot whales, or five body lengths for seals. *Re*-sightings of the same individual or group were recorded as such. aMMOs also recorded if they received an IR alert that corresponded with a sighting, and if that alert was received before or after a visual sighting was made (i.e., did the alert assist the aMMO in making the sighting?).

2.3. Passive acoustic monitoring

The PAM system was monitored by both experienced and inexperienced PAM (ePAM and iPAM, respectively) operators. The three ePAM operators all had 6+ years' experience in the field of marine mammal research and PAM, and all had expertise in real-time bioacoustics monitoring and data analysis. ePAM operators had 4+ years experience using *PAMGuard* software in real-time at sea, and were familiar with THA operations and maintenance for research and/or seismic industry applications. The two iPAM operators were biologists with 15+ years' work experience with marine mammals, each had completed two or more shifts as an MMO in offshore seismic surveys, but neither had prior experience with THA or *PAMGuard*. Pre-survey training for the iPAM operators used course materials from the Biowaves' Passive Acoustics Technology Training Course (www.biowaves.net/passive-acoustic-technology-training/). The training consisted of one day of independent review (materials on acoustic theory, digitizing sound, noise and filters, marine mammal sounds, and

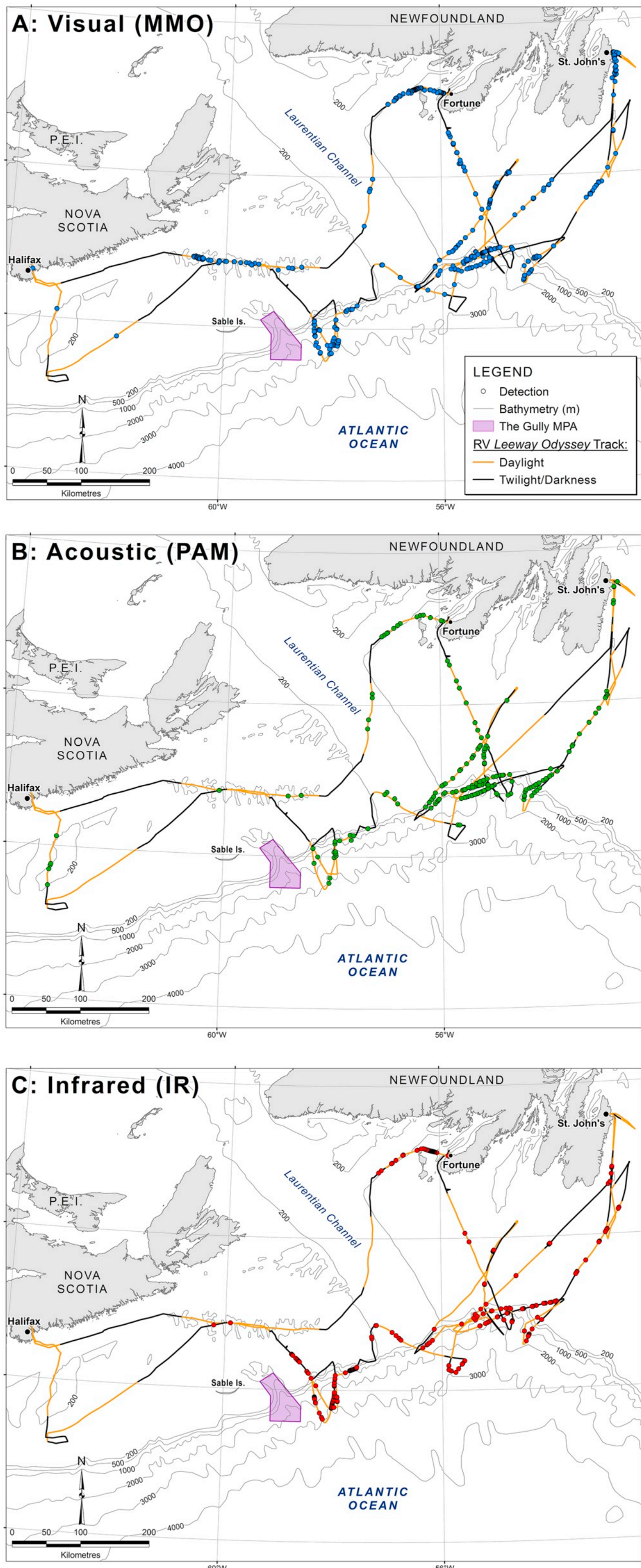

Fig. 2. Marine mammal detections made aboard the RV *Leeway Odyssey* during 30 July to 23 August 2017. (A) MMO detections were made during daylight hours. (B) PAM detections were made daily from ca. 04:00 to 24:00 (local time). All PAM detections, including those not localized, are plotted. (C) The IR system ran continuously throughout the survey.

PAMGuard introductory training modules) and a one day in-person training session led by Bio-Waves staff (hardware review and hands-on practice with localization methods in *PAMGuard*). Additional at-sea training for iPAM operators occurred during the initial days of the survey whereby ePAM operators mentored iPAM operators.

The THA consisted of two pairs of hydrophone elements, pre-amplifier circuit boards, and a pressure sensor, all housed in a flexible tube filled with castor oil. A pair of high-frequency hydrophones (High Tech, Inc. HTI-99-UHF elements; effective frequency response from 2 Hz to 250 kHz) spaced 0.5 m apart were positioned mid-way between a pair of mid-frequency hydrophones (APC International 42-1021 elements; effective frequency response from ~1 to 100 kHz) that were spaced 3 m apart. An analog pressure sensor (Kellar 7SE) was located at the trailing end of the array. Preamplifiers for the high frequency hydrophones were designed and integrated by the supplier (HTI) with 38 dB of gain and a high-pass filter with a corner frequency of 500 Hz. Preamplifiers for the mid-frequency hydrophones were designed and fabricated by Biowaves Inc., and had 40 dB of gain, a single-pole high-pass filter with a corner frequency of 250 Hz, and a single-pole low pass filter with a corner frequency of 35 kHz. An electromechanical tow-cable was attached to the array and was weighted with lead rope to sink it below the water's surface. The array was deployed 300 m behind the stern of the vessel using a large block and a hydraulic winch and drum system.

The pre-amplified analog signals from the hydrophones were passed from the array up the copper-wire tow-cable and fed into an acoustic processing system (APS) for signal conditioning, digitization, and subsequent monitoring and recording (Rankin and Barlow, 2011). The APS was powered by a 12 V DC battery bank that was independent of the vessel's power system. Additional measures taken to minimize noise in the acoustic signal included electronic shielding of all acoustic analog cables from the array to the APS and avoiding the use of high-power electronics and radio-wave emitting (e.g., VHF radio) devices in the acoustics lab on the vessel.

In the APS, analog signals were amplified and filtered to reduce low-frequency noise using an adjustable high-pass filter and amplifier (Magrec; up to 20 dB gain). Signals were then split and sent to independent monitoring systems for the ePAM and iPAM operators. For ePAM operators, high-frequency hydrophone signals were digitized using a SAIL DAQ sound card (SMRU Instrumentation) sampling at 500 kHz (i.e., high frequency signal), and mid-frequency hydrophone signals were digitized using an RME digital audio-interface (model FireFace UCX), sampling at 192 kHz (i.e., mid frequency signal). For iPAM operators, only mid-frequency signals were digitized using an RME sound card (model BabyFace) sampling at 192 kHz; iPAM operators did not monitor the high frequency signal.

PAMGuard software was used to record, visualize, and analyze digitized signals in real-time (version 1.15.11; Gillespie et al., 2008; www.pamguard.org). In addition to bioacoustic data collection, *PAMGuard* also simultaneously logged GPS data, and provided forms for operators to enter information, such as on/off effort, filter and amplifier settings, configurations used, notes about encounters, and other ancillary data.

Incoming signals were always monitored in real-time by ePAM operators when the THA was deployed (ca. 04:00 to 24:00 daily; all times given as local daylight-saving time, LT). iPAM operators monitored the acoustic signal daily from ca. 05:00 to 21:00 during the last two weeks of the survey. Shift lengths ranged from 2 to 3.7 h. The iPAM and ePAM operators worked independently of one another (i.e., at spatially separated stations within the acoustic lab) during data collection and analysis, with the exception of occasions when iPAM operators requested technical assistance from ePAM operators related to hardware or software issues (e.g., malfunctions or computer crashes). Because our priority was to compare detections/localizations made by ePAM and iPAM operators within our limited survey window, we did not want the iPAM operators' lack of experience troubleshooting and maintaining the PAM system to jeopardize the amount of acoustic data collected, or to preclude them from making detections. Additionally, the ePAM operators were tasked with retrieving and deploying the array, monitoring and maintaining all hardware (including the power system), and data-

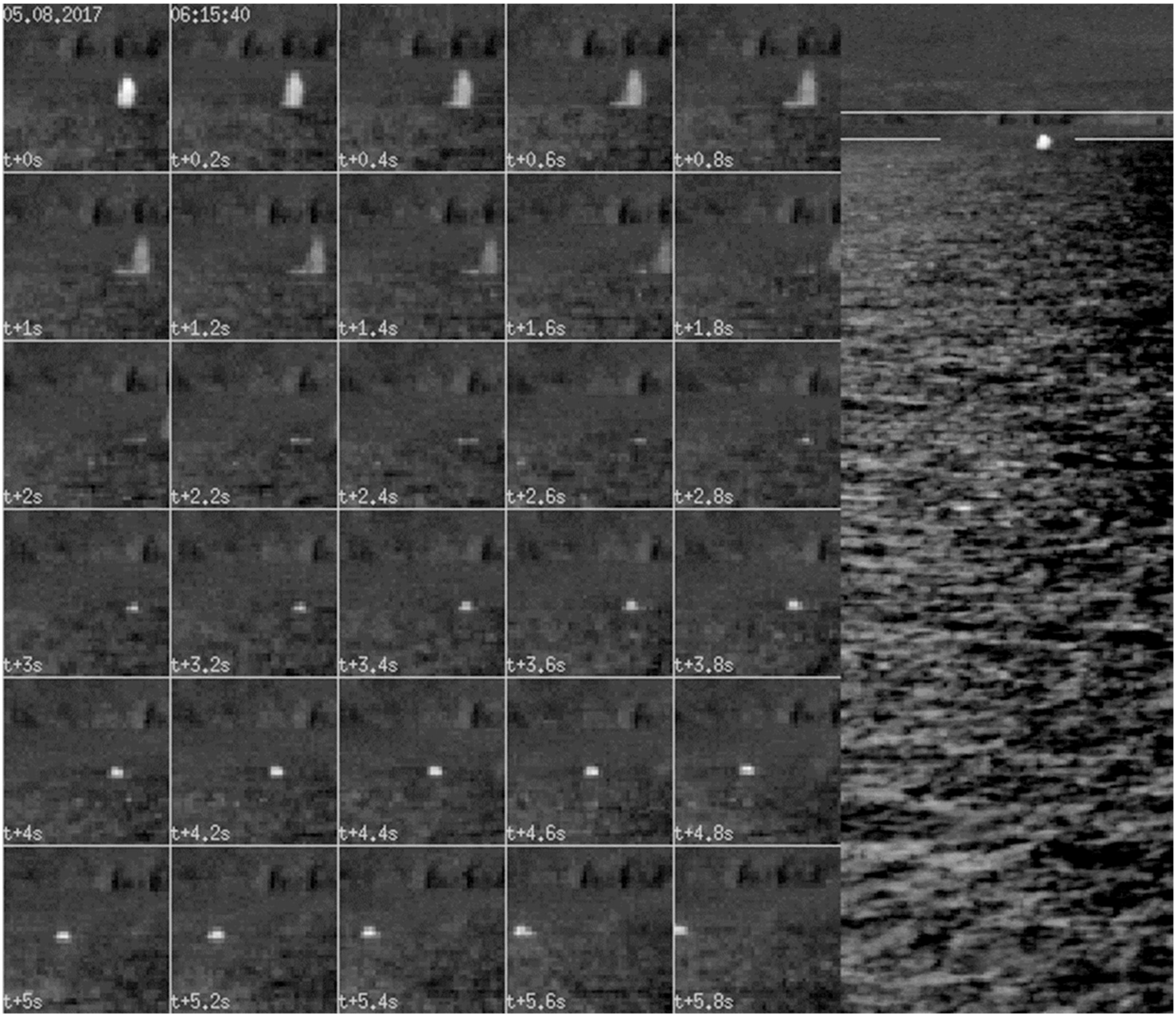

Fig. 3. IR imagery of an automatic marine mammal detection. Snapshots at 0.2 s intervals are displayed at left, and a six-second video clip of the detection plays on repeat in the vertical panel at right. A blow (tall white image) is visible in the vertical panel and in snapshots 0 to 1.6 s, followed by the back of the whale (smaller white image) in snapshots 2.8 to 5.8 s.

management.

When on effort, ePAM operators visually and aurally monitored the spectrogram and time-bearing displays consisting of a frequency band of ca. 500 Hz – 250 kHz. iPAM operators were limited to monitoring only the mid-frequency hydrophones, which consisted of the ca. 500 Hz – 35 kHz frequency bandwidth. Acoustic detections were not restricted to specific signal to noise ratio (SNR) thresholds but did require that a PAM operator visually (and aurally when within human hearing threshold) detect the animal or group of animals on the spectrogram. Click and whistle moan detectors required this spectrogram visual check to eliminate the possibility of a false detection. Click detectors incorporated an amplitude threshold which effectively reduced the occurrence of false detections from noise being misclassified as marine mammal clicks. A minimum of 10 echolocation clicks or five whistles was defined as the threshold to record it as a detection. When unknown sounds were observed on the spectrogram, detections were reviewed to reduce the misclassification of noise as marine mammal vocalizations.

PAM operators classified each detection to the most specific taxonomic rank possible. *PAMGuard's* “Click Detector” module and associated “Click Classification” feature were configured to monitor for a range of echolocating species. Click classifiers were enabled to differentiate detected click trains into categories with associated colors that were displayed within the time-bearing display of the Click Detector window. They were configured to detect peak frequencies that fell within specific frequency bands: 2–15 kHz, 15–30 kHz, 30–50 kHz, 30–50 kHz with an upsweep in the click, 50–80 kHz and 100–140 kHz. For most classifiers, one of several species may be detected. Classifiers were therefore used to help organize the clicks so that an operator could evaluate the click characteristics, and if possible, assign to species group. For example, the 100–140 kHz classifier could detect click trains produced by harbor porpoise (*Phocoena phocoena*), Dall's porpoise (*Phocoenoides dalli*), dwarf sperm whale (*Kogia sima*), etc. This classifier was useful for differentiating these species from beaked whales, dolphins, and sperm whales, but could not be used to identify the exact species that produced the click train. Alternatively, an operator may have simply indicated that the vocalizing animal/group made a narrow band high frequency (NBHF) call as real-time species identification is sometimes difficult. Whistles and low frequency moans were detected by visually monitoring the 500 Hz – 35 kHz band in a spectrogram window.

To acquire localizations, the PAM operator selected clicks from the time-bearing display of the Click Detector window, or whistles from the spectrogram, and assigned them to a click train or group. *PAMGuard* plotted bearings associated with these click trains or groups on a map, and PAM operators inspected these maps for the presence of converging bearings to assign a localization to an individual or group of animals. These data were then used, via target motion analysis (Leaper et al., 1992), to estimate the location of the vocalizing animal or group of animals. PAM operators manually measured the perpendicular distances from the trackline to the localization using a measuring tool that was part of the *PAMGuard* software. A limitation of using only two hydrophones in a linear array is that localizations were subject to a left-right ambiguity. Therefore, mirror-image localizations were estimated on either side of the trackline. PAM operators also recorded detections that did not result in a localization.

2.4. Infrared (IR) imaging system

The rotating IR camera (FIRSTnavy sensor, Rheinmetall Defence Electronics GmbH, RDE) and actively stabilized gimbal were mounted on a custom-built platform welded onto the vessel (Fig. 1B). The IR camera had a viewing height of 7.8 m above the vessel's waterline, and a 244.5° field of view (FOV; from −120.9° to 123.6°, where 0° is looking forward). The IR camera FOV was slightly obstructed by vessel superstructure ahead and to the sides of the vessel, similar to the obstructions encountered by the MMOs. The FIRSTnavy sensor images radiances in the 8 – 12 μm wavelength band (LWIR) and is cooled to 84 K using a Sterling cooler. It scans 360° horizontal x 18° vertical at 5 revolutions per second, providing a 5-Hz video stream at horizontal and vertical resolutions of 0.05°/pixel and 0.03°/pixel, respectively.

The IR system was operated continuously while the survey was underway. However, IR data collected during the night after the THA was retrieved and PAM operators had gone "off effort" were excluded from the analysis because during the overnight hours the vessel periodically increased speed to 10 kn for engine maintenance. Data acquisition and processing were performed with custom developed software (*Tashtego*). *Tashtego* utilizes a multi-step detection and classification approach that was developed with data collected during previous expeditions (Zitterbart et al., 2020). *Tashtego* makes IR detections by tracking contrast in radiance in the IR video stream and applying a set of heuristic rules designed to reduce the number of non-marine mammals (e.g., birds and vessels) detected. Nevertheless, automatic IR detections include both true and false positives. An engineer oversaw the functioning of the IR system, and adjusted the detection threshold when the automatic detection rate increased such that the frequency of alerts was a hindrance to aMMOs.

Tashtego simultaneously logged vessel position and heading. It also recorded the bearing, and instantaneously estimated the distance, to each automatic detection. Though the gimbal compensated for up to 12° roll and 10° pitch, we often encountered sea conditions that exceeded these limits. During times without working gimbal stabilization (see Videoclip S1 in Supplementary material for an example of an instance where gimbal capacity was exceeded), detections as well as distance estimates by *Tashtego* are unreliable. Unfortunately, the IR system was not designed to record times during which the gimbal capacity was exceeded, and we were therefore unable to identify and eliminate these periods of time from our dataset. We accounted for this by including only bearings to the automatic IR detections in our analysis.

2.5. Terminology used to describe detections

In this paper, we use different terms to refer to detections made using visual, acoustic, and IR imaging methods. Marine mammal detections made by MMOs are referred to as "MMO detections". Acoustic detections of marine mammals are referred to as "PAM detections", or if localization was possible, "PAM localizations". The IR imaging system was used to make "automatic IR detections". After human-verification, automatic IR detections were categorized as "true *or* false positive IR detections".

2.6. Environmental data

MMOs recorded, when on effort during daytime, the following environmental data every half hour and when conditions changed: precipitation type (rain, drizzle, fog or none), wind force (Beaufort Wind Force), and visibility (estimated viewing distance to maximum of 10 km). Air and sea surface temperature (SST) data from the Banquereau buoy at 44.240 N 57.100 W were downloaded from http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/waves-vagues/data-donnees/data-donnees-eng.asp?medsid=C44139; data were logged at 3-h intervals.

2.7. Data analysis

Analyses were performed in *R 3.5.1* (R Core Team, 2018) or *Matlab R2017b* (The MathWorks Inc., 2017), and results were deemed significant at $\alpha = 0.05$.

In order to identify which automatic IR detections were true detections of marine mammals and which detections were false positives, all automatic IR detections were human-verified. An initial review and classification were done by MMOs while still at sea (but not while making observations). Classification was subjective and based on the overall appearance of the IR anomaly in a six-second video clip (Fig. 3). The subset of detections initially classified as true positives was subsequently reviewed by three independent MMOs and classified to the most specific taxonomic rank in which two or more reviewers had confidence.

Duplicate true positive IR detections (i.e., multiple automatic detections made during a single blow or dorsal fin surfacing) were removed from the dataset. This was accomplished by identifying detections made within two seconds and five bearing degrees of one another and retaining only the first of these.

Data were analyzed at the level of individual detection or "encounter". For MMOs and the IR system, single cues (e.g., a blow or a dorsal fin) were considered single detections. For the PAM system, a detection was defined as a series of vocalizations (e.g., click trains or whistles associated closely in time and/or space) and considered by the operator to be made by an individual or group of marine mammals, and used to make a localization (if possible). Analysts assigned detections to encounters during post-processing. Encounters were defined to include detections made using one or more methods, and consisted of repeat detections (or localizations) of what was likely the same individual or group of marine mammals (i.e., "re-sightings") or included multiple groups of animals in the same general vicinity if they occurred within ca. 5 to 10 min of one another (e.g. groups of dolphins approaching and bow-riding the vessel, humpbacks engaged in surface activity). Factors considered when assigning detections to an encounter included species, group size, detection location (if available), travel behavior, and any comments recorded by MMOs or PAM operators. Encounters sometimes included more than one species, e.g., some encounters included both dolphins (one or more species) and pilot whales. Encounters also sometimes included animals that were classified differently by different observers/operators (e.g., humpback whale and unidentified baleen whale).

Detections made via MMO, PAM, and IR methods were summarized across categories of three environmental parameters (precipitation, Beaufort wind force, and visibility) for times when the three methods were employed concurrently. A qualitative comparison of detection rates is presented given the small sample sizes (i.e., amount of effort) for many of the environmental categories.

The proportions of detections made to the level of species were compared for different methods/experience levels with 1-sided Fisher's exact test (McDonald, 2014). One-sided tests were used because MMOs and experienced observers/operators were expected to classify more detections to the species level than PAM operators and inexperienced observer/operators, respectively. Post-hoc tests were assessed using a Bonferroni-modified alpha. Comparisons for eMMOs vs. the iMMO were made for all detection distances combined, as well as detection distances ≤500 m and >500 m. These distance bins were examined because 500 m is the minimum required radius for the safety zone specified in many mitigation guidelines (Acosta et al., 2017; DCE et al., 2015; DFO, 2008; Weir and Dolman, 2007).

Detections of marine mammals made via different detection methods and by MMOs and PAM operators with different levels of experience were compared by calculating conditional probabilities (Eq. (1)).

$$P(A \mid B) = \frac{P(A \bigcap B)}{P(B)} \tag{1}$$

Conditional probabilities were calculated at the level of encounter, and only encounters that occurred during times of concurrent effort for the methods/experience levels being compared were included in the calculations. Conditional probabilities involving IR detections were calculated for all cetacean encounters combined, and separately for large whales and small cetaceans (which were mutually exclusive groups). Baleen and sperm whales were included in the "large whale" category, while all other toothed whales were categorized as "small cetaceans". Conditional probabilities involving PAM detections used only detections that were localized (i.e., PAM localizations), and were not calculated for baleen whales given that these were generally not detectable by the THA. Conditional probabilities for the comparison of eMMOs and the iMMO were calculated for all detection distances combined, as well as detection distances ≤500 m and >500 m.

Radial distributions of detections around the vessel were compared using Watson's U^2 test for homogeneity (package 'CircStats'; Lund and Agostinelli, 2018). The radial distributions of MMO and IR detections were compared at the level of individual detection in order to characterize the extent of the FOV that could be monitored using these methods. The radial distributions of MMOs vs. PAM and eMMO vs. iMMO were compared at the level of encounter in order to characterize where these types of observers typically detected marine mammals.

For a given encounter, initial detection distance and timing were compared for different observer types. Initial detection distances for encounters recorded by eMMO, aMMO, and ePAM were compared using an ANOVA and the DTK post-hoc test (package 'DTK'; Lau, 2013), whereas a 1-sided paired *t*-test was used for the comparison of eMMOs vs. iMMO. A Wilcoxan signed rank test was used to compare initial detection distances for ePAM and iPAM because the distribution of differences in distances between the two methods was skewed (McDonald, 2014). The timing of the initial localization for encounters recorded by MMOs (eMMOs and aMMOs combined) and ePAM operators was compared using a Wilcoxon signed rank test, whereas eMMO vs. iMMO and ePAM vs. iPAM were compared using 1-sided paired *t*-tests.

3. Results

Environmental conditions were generally favorable for sighting marine mammals. During the survey, there was limited precipitation (including fog), visibility was predominantly >4 km, and sea state was generally at or below Beaufort wind force 4 (Table 1). Air temperature and SST recorded by the Banquereau buoy averaged 18.49 ± 0.95 °C and 18.23 ± 0.71 °C, respectively (mean ± SD) during 31 July to 23 August 2017.

A total of 1981 marine mammal detections (all methods combined) was made over the course of the survey (Table 2, Fig. 1, Table S1 in Supplementary material). Most effort and detections were during daylight hours (Table 2).

3.1. Infrared (IR) system functioning

The *Leeway Odyssey* is the smallest vessel on which the AIMMMS has been installed to date, and the low platform height where the sensor was installed, 7.8 m compared to >15 m on other installations, in combination with rolling seas, often exceeded the limit of mechanical stabilization by the gimbal. During these "stall" times, the camera FOV differed from one frame to the next, thereby removing pixel correspondence between frames, which is the basis for the automatic detection algorithm. By design, the detection algorithm cannot function on a non-stabilized video feed, and therefore performed poorly (i.e., had an increased probability of making false positive detections and decreased probability of making true positive detections) during these times. This lack of stabilization was apparent to MMOs when manually reviewing video clips because the horizon in the imagery did not remain stable (Videoclip S1 in Supplementary material). The IR engineer noted that this occurred during a substantial proportion of time. As the system was not designed to log periods when the gimbal's limits were exceeded, these periods could not be excluded from analyses.

The IR system made 9189 automatic detections over the course of the survey; 1501 (16.3%) of these were initially classified as true positives (Table 3A). After undergoing the second review, 74 of these were re-classified as false positives (Table 3B), thereby reducing the total number of true positives to 1427 (15.5%). The majority of false positives were birds and waves (41.4% and 22.8% of all automatic detections, respectively; Table 3, Videoclips S2 and S3 in Supplementary material). Shearwaters were the most problematic group of birds, in terms of causing false positive IR detections. Shearwaters were automatically detected when rafting on the water's surface during calm seas; landing or scooting across the water's surface prior to getting airborne during calm to moderate sea conditions; and soaring low over the water during windy, large wave conditions (when they would disappear behind the crest of a wave and then re-emerge). Shearwater species encountered were ca. 90% Great Shearwaters (*Puffinus gravis*), followed by Sooty (*Ardenna grisea*), Cory's (*Calonectris borealis*), and Manx (*P. puffinus*), in descending order. Larger birds, such as gulls and gannets, were also detected on the water.

True positive IR detections received final broad classifications of whale (223, primarily large whales; Videoclips S4 to S8 in Supplementary material), dolphin (861, includes small and large dolphins and pilot whales; Videoclips S9 to S11 in Supplementary material), and cetacean (343). Whereas four automatic detections received a final classification (i.e., agreed upon by two or more reviewers) of sperm whale (Table 3B), an additional 20 detections were classified to the species level (sperm whale (4), humpback whale (16)) during the second round of review. However, this level of confidence was held by only a single reviewer in each instance; thus, these detections were classified according to majority rule as baleen whale (6), baleen or sperm whale (5), unidentified whale (2), cetacean (1), and dolphin (6).

3.2. Real-time IR system use by MMOs while making observations

aMMOs were on effort for 184.3 h during the survey (Table 2A) and made a total of 146 unique detections (i.e., re-sightings excluded; Table 4). Of these detections, 144 were classified as cetaceans, and two were classified as unidentified seals. 21.3% of these detections (Table 4) were associated with an IR alert in real-time by the aMMO. Of the cetacean detections, 15 were observed after receiving an IR alert, 16 were observed by the aMMO with the subsequent receipt of an IR alert, and 113 had no associated IR alert in real-time (Table 4). IR alerts associated with detections were primarily for toothed whales (24 of 146

Table 1
Environmental conditions recorded by observers during daylight hours while conducting a survey for marine mammals offshore of Atlantic Canada, August 2017.

Environmental parameter	Parameter categories and percentage of daylight hours in each category
Precipitation	None (88.1%); Rain (1.8%); Drizzle (1.5%); Fog (7.8%); Mix (0.7%)
Wind force	0-1 (5.4%); 2 (20.2%); 3 (26.6%); 4 (17.4%); 5+ (30.4%)
Visibility (km)	≤0.5 (3.2%); >0.5 & ≤1 (1.7%); >1 & ≤2 (2.6%); >2 & ≤4 (4.7%); 4+ (87.7%)

Table 2
Summary of all data collection effort and marine mammal detections made by MMOs, PAM operators, and via IR imaging. Daylight hours were from ca. 05:30 to 20:00 LT. PAM and IR data were collected from ca. 04:00 to 24:00 LT each day and include times when the IR system gimbal stabilization capability was exceeded. Duplicate IR detections of the same cue (e.g., blow) have been excluded. Repeat detections (i.e., "re-sightings") of individual animals/groups are included.

	Daylight			Twilight/Darkness		
Detection method[1]	Effort (h)	No. of detections	Detection rate (/h)	Effort (h)	No. of detections	Detection rate (/h)
A.MMO detections						
eMMO	185.7	241	1.3	3.5	1	0.3
iMMO	88.3	80	0.9	0.2	0	0
aMMO	177.7	198	1.1	6.6	1	0.2
Totals	451.7	519	1.1	10.3	2	0.2
B.PAM detections						
ePAM	189.1	212	1.1	52.4	45	0.9
iPAM	143.5	224	1.6	10	27	2.7
Totals	332.6	436	1.3	62.4	72	1.2
C.Infrared (IR) detections						
Rotating IR camera	287.7	841	2.9	112.4	111	1.0
Grand totals, all methods combined	1072	1796	1.7	185.1	185	1.0

[1] eMMO = experienced MMO, iMMO = inexperienced MMO, aMMO = assisted MMO, ePAM = experienced PAM operator, iPAM = inexperienced PAM operator.

Table 3
Retrospective classification (by humans) of automatic IR detections.

True positives		False positives	
A. Initial classification of all automatic IR detections			
Blow	209	Birds	3804
Body	851	Waves	2093
Dolphin	415	Sun, cloud, unknown	1117
Breach, splash	26	Objects at sea	592
		Land	82
Totals	1501		7688
B. Final classification of initial true positive IR detections			
Sperm whale	4	Bird	12
Baleen whale	38	Wave	9
Baleen or sperm whale	75	Unknown	53
Unidentified whale	106		
Dolphin, small	21		
Dolphin, large	3		
Dolphin	837		
Cetacean	343		
Totals	1427		74

detections; 16.4%). Neither seal detection was associated with an IR alert.

3.3. Comparison of MMO, PAM, and IR detections

Visual inspection of the data revealed that detection rates changed with environmental conditions, and that the change observed varied with detection method (Table 5). ***Precipitation*** was rarely experienced during the survey, and accordingly, the greatest number of detections were made during times without precipitation (Table 5A). While PAM detection rates were the same for times with no precipitation vs. times with precipitation (rain, drizzle, and fog, combined), MMO and IR detection rates were greater with no precipitation vs. times with precipitation. When precipitation was present (rain, drizzle, and fog,

Table 4
Marine mammal detections made by aMMOs, i.e., with access to automatic detection alerts from the IR imaging system. Repeat detections (i.e., "re-sightings") of individual animals/groups are excluded.

Marine mammal	Number of detections associated with IR alerts		
	Alert preceded detection	Alert received after detection	No IR alert associated with detection in real-time
A.Baleen whales (including unidentified whales)			
Blue whale	0	0	2
Fin whale	0	1	2
Minke whale	0	0	1
Humpback whale	0	1	11
Unidentified baleen whale	3	1	9
Unidentified whale	0	1	3
Total no. and % of all marine mammals	3 (2.1%)	4 (2.7%)	28 (19.2%)
B.Toothed whales			
Long-finned pilot whale	1	0	6
White-beaked dolphin	0	0	5
Atlantic white-sided dolphin	0	0	2
Short-beaked common dolphin	6	3	33
Risso's dolphin	1	2	0
Striped dolphin	0	1	0
Unidentified dolphin	3	5	36
Sperm whale	0	1	3
Unidentified odontocete	1	0	0
Total no. and % of all marine mammals	12 (8.2%)	12 (8.2%)	85 (58.2%)
C. Unidentified seal	0	0	2
Grand totals and % of all marine mammals	15 (10.3%)	16 (11.0%)	115 (78.8%)

Table 5
MMO, PAM, and IR detections of marine mammals made during concurrent effort and categorized according to environmental conditions recorded by MMOs. Effort includes times when the IR system gimbal stabilization capability was exceeded. Duplicate IR detections of the same cue (e.g., blow) have been excluded. Repeat detections (i.e., "re-sightings") of individual animals/groups are included.

Environmental parameters and categories	Observation effort (h)	Marine mammal detections according to type of effort			Marine mammal detection rates (/h) according to type of effort		
		MMO	PAM	IR	MMO	PAM	IR
A. Precipitation							
None	178.8	426	399	741	2.4	2.2	4.1
Rain	0.3	1	1	0	3.3	3.3	0.0
Drizzle	1.4	2	6	0	1.4	4.3	0.0
Fog	16.7	16	34	7	1.0	2.0	0.4
RDF[1]	18.4	19	41	7	1.0	2.2	0.4
B. Beaufort wind force							
0–1	10.6	1	0	0	0.1	0.0	0.0
2	39.1	67	60	137	1.7	1.5	3.5
3	60.4	140	94	526	2.3	1.6	8.7
4	27.8	131	135	71	4.7	4.9	2.6
5+	59.2	106	151	14	1.8	2.6	0.2
C. Visibility (km)							
≤ 0.5	6.9	6	12	2	0.9	1.7	0.3
> 0.5 & ≤ 1	3.8	2	13	1	0.5	3.4	0.3
> 1 & ≤ 2	5.1	8	10	0	1.6	2.0	0.0
> 2 & ≤ 4	7.1	4	12	0	0.6	1.7	0.0
≤ 4	22.9	20	47	3	0.9	2.1	0.1
> 4	174.3	425	393	745	2.4	2.3	4.3
Totals	197.2	445	440	748	0.9	1.7	0.3

[1] RDF = rain, drizzle, and fog combined.

combined), PAM yielded a detection rate that was greater than twice the rate for the MMOs, and five times the rate for the IR system. The IR system made no detections during periods of rain or drizzle.

A little more than half of the daytime survey effort occurred in conditions with ***Beaufort wind force*** ≤ 3 (Table 5B). MMO and PAM detection rates both increased with increasing wind force up to Beaufort wind force 4, and then decreased after that. MMO detection rates were greater than PAM detection rates at Beaufort wind force ≤3 but were lower than PAM detection rates at Beaufort wind force ≥5. IR detection rates were greatest during Beaufort wind force levels of 2–3 and were greater than the corresponding MMO and PAM detection rates. IR detection rates decreased at Beaufort wind force ≥4 and were lower than the corresponding MMO and PAM detection rates.

MMOs estimated that ***visibility*** was >4 km during most of the survey (Table 5C). The greatest number of detections were made during these relatively good visibility conditions, compared to all lower levels of visibility combined, for all methods. When visibility was ≤4 km, PAM methods yielded detection rates that were greater than for either the MMOs or the IR system. The IR system had the highest overall detection rates when visibility was >4 km.

Detections made by MMOs and the IR system were observed to overlap the most consistently. The probability that detections made by MMOs were also made by the IR system, and vice versa, ranged from 20% to 34%. Of these, the greatest probabilities were for MMOs detecting large whales given that they were also detected by the IR system (34%, Table 6). PAM detections overlapped to the greatest extent with MMO detections. These overlaps ranged from a 25% probability that a small cetacean was detected by an MMO given that it was detected by the THA to a 47% probability that a small cetacean was detected by the THA given that it was also detected by an MMO (Table 6). In general, the overlap in detections among methods was lowest for PAM and the IR system (range in conditional probabilities: 9% to 13%; Table 6).

The radial distribution of detections around the vessel differed significantly for IR vs. MMO detections (Watson's $U^2_{1020,\ 614} = 1.75$, $p < .001$). MMO detections were relatively evenly distributed around the front and sides of the vessel, whereas the greatest proportion of IR detections were made along the starboard side of the vessel. A small number of MMO detections made towards the stern of the vessel were not in the IR camera's FOV.

Table 6
Conditional probabilities for MMO detections, PAM localizations, and IR detections of cetacean when all three methods were employed concurrently (including times when IR system gimbal stabilization capability was exceeded). Large whales include baleen and sperm whales, and small cetaceans include all other toothed whales.

	Conditional probabilities		
	All cetaceans	Large whales	Small cetaceans
P(MMO|IR)	0.21	0.34	0.20
P(MMO|PAM)	0.28	NA[1]	0.25
P(IR|MMO)	0.28	0.21	0.26
P(IR|PAM)	0.13	NA	0.09
P(PAM|MMO)	0.42	NA	0.47
P(PAM|IR)	0.12	NA	0.11

[1] Most baleen whale calls were below the 250 Hz high-pass preamp filter and between 250 and 500 Hz where ship sound consistently masked biological sounds and are therefore marked as "NA".

3.4. Comparison of eMMO, aMMO, and PAM detections

During 80 h of concurrent effort by the eMMO, aMMO and ePAM operators, the eMMO and ePAM operator each made more detections than did the aMMO. Of the detections made by the ePAM operator, slightly more than half were localized (Table 7). During the concurrent effort, MMOs (experienced and assisted) detected both baleen and toothed whales whereas the ePAM operator detected only toothed whales (Table 7).

MMOs (experienced and assisted) classified more detections to the species level than did ePAM operators (1-sided Fisher's exact tests, all $p < .001$). The only species classified by ePAM operators during the concurrent effort was the sperm whale, whereas MMOs classified species of both baleen and toothed whales (Table 7). Single detections of a humpback whale and a Risso's dolphin (*Grampus griseus*) were made by an ePAM operator during the survey, but were not made at a time when both the eMMO and aMMO were also on effort, and are therefore not included in this analysis of data from concurrent effort.

Of the 72 toothed whale encounters detected (and localized) during concurrent effort by eMMOs, aMMOs, and ePAM operators, 17 were recorded by all three types of observers (Table 8A). More toothed whale encounters were recorded by ePAM operators than by either eMMOs or aMMOs (Table 8A). It was also more likely that an ePAM operator would localize toothed whales also located visually by an MMO (56%, Table 8B) than an MMO was to locate toothed whales also localized by ePAM (39%; Table 8B). Twenty-eight toothed whale encounters were recorded by only ePAM operators during this time (Table 8A).

Twelve baleen whale encounters were recorded by MMOs during concurrent effort by eMMOs, aMMOs and ePAM operators. The probability that a baleen whale detected by an aMMO was also detected by an eMMO was marginally higher (62%) than the probability that a baleen whale detected by an eMMO was also detected by an aMMO (56%; Table 8B).

The distribution around the vessel of initial detections for encounters recorded by the MMOs (eMMO and aMMO combined) differed significantly from the distribution of encounters localized by ePAM operators (Watson's $U^2_{196,\ 102} = 2.45, p < .001$). The majority of ePAM localizations were made to either side of the vessel whereas most MMO detections were made to the front and both sides of the vessel. Distance to the initial detections for encounters also differed significantly among

Table 7
Marine mammal detections made by eMMOs, aMMOs, and ePAM operators during 80 h of concurrent effort (including times when the IR system gimbal stabilization capability was exceeded).

Observer type / Marine mammal	Number of detections: eMMO	aMMO	ePAM [no. of detections localized]
A.Baleen whales (including unidentified whales)			
Blue whale	1	1	NA[1]
Fin whale	3	3	NA
Minke whale	0	1	NA
Humpback whale	1	1	NA[2]
Unidentified baleen whale	6	4	NA
Unidentified whale	4	0	NA
Total (no. classified to species)	15 (5)	10 (6)	NA
B.Toothed whales			
Long-finned pilot whale	4	5	0
Blackfish (i.e., pilot or killer whales)	0	0	9 [3]
Atlantic white-sided dolphin	1	1	0
Short-beaked common dolphin	36	37	0
Common dolphin spp.	0	0	5 [1]
Unidentified dolphin	29	18	49 [33]
Unidentified dolphin or beaked whale	0	0	7 [4]
Sperm whale	4	4	20 [13]
Total (no. classified to species)	74 (45)	65 (47)	90 [54] (20)
C.Seals			
Unidentified seal	1	1	0
Grand total no. of detections	90	76	90 [54]

[1] Baleen whale calls below the 250 Hz high-pass preamp filter and between 250 and 500 Hz where ship sound consistently masked biological sounds are marked as "NA".
[2] Humpback whale calls above 500 Hz and with received levels above persistent ship engine sound had the potential to be detected on the linear array.

Table 8
Number and conditional probabilities for marine mammal encounters recorded eMMOs, aMMOs, and ePAM operators during 80 h of concurrent effort (including times when the IR system gimbal stabilization capability was exceeded). Only ePAM detections that were localized are included. "All cetaceans" includes unidentified whales.

Observer type	All cetaceans	Baleen whales	Toothed whales
A. *Number of encounters recorded by*			
eMMO only	16	4	8
aMMO only	11	3	8
ePAM only	28	NA[1]	28
eMMO and aMMO	12	5	7
eMMO and ePAM	2	NA	2
aMMO and ePAM	2	NA	2
eMMO and aMMO and ePAM	17	NA	17
Total no. of encounters	88	12	72
Summary: eMMO with or without other methods	47	9	34
Summary: aMMO with or without other methods	40	8	34
Summary: ePAM with or without MMO	49	NA	49
B. *Conditional probabilities (no. of encounters used in calculation)*			
P(eMMO|aMMO)	0.69 (60)	0.62 (12)	0.71 (44)
P(eMMO|ePAM)	0.39 (77)	NA	0.39 (64)
P(aMMO|eMMO)	0.62 (60)	0.56 (12)	0.71 (44)
P(aMMO|ePAM)	0.39 (72)	NA	0.39 (64)
P(ePAM|eMMO)	0.40 (77)	NA	0.56 (64)
P(ePAM|aMMO)	0.45 (72)	NA	0.56 (64)

[1] Most baleen whale calls were below the 250 Hz high-pass preamp filter and between 250 and 500 Hz where ship sound consistently masked biological sounds and are therefore marked as "NA".

Table 9
Detections classified to species level during 43.5 h of concurrent effort by eMMOs and the iMMO. The classification during the initial detection was used when the same individual/group of marine mammals was "re-sighted".

	Number of detections classified to species					
	All distances		≤ 500 m		> 500 m	
Observer type	Yes	No	Yes	No	Yes	No
eMMO	39	8	24	1	15	7
iMMO	15	9	12	5	3	4
p-values for 1-sided Fisher's exact text	0.055		0.032		0.223	

observer types ($F_{2,\ 128} = 20.98$, $p < .001$). eMMOs and aMMOs made detections at the same mean initial distance (0.8 km), which was significantly less than that for ePAM operators (mean = 2.6 km). The initial detection for encounters made by MMOs (eMMO and aMMO combined) was on average made marginally before ePAM operators, though this difference was not significant (Wilcoxon signed rank test: V = 73, p = .24; mean difference in timing of detection = 59.4 s).

3.5. Experienced vs. inexperienced MMOs

Over the course of the 43.5 h of effort during which eMMO and iMMO shifts overlapped, eMMOs made more detections than the iMMO, and classified significantly more detections to the level of species than did the iMMO at detection distances ≤500 m from the vessel (1-sided Fisher's exact test, p = .032; Table 9). At distances > 500 m, the proportion of detections classified to species level did not differ significantly between eMMOs and the iMMO (p = .223; Table 9).

In general, the iMMO classified fewer baleen whales to species level than the eMMO. Of the 14 encounters recorded by both eMMO and iMMO, all were classified to the species level by the eMMO. Four of the encounters were of baleen whales: a fin and minke whale classified by the eMMO were classified by the iMMO as "unidentified baleen whale", and a fin and humpback whale classified by the eMMO were eventually also classified as the same species by the iMMO during a re-sighting (i.e., iMMO species ID did not match eMMO species ID during initial sighting). There was more agreement between iMMO and eMMO classifications for smaller toothed whales than larger baleen whales. Six of the ten toothed whale encounters recorded by both eMMO and iMMO had matching classifications (dolphins or pilot whales). Two of the ten encounters had multiple species classified by the eMMO, some of which matched the iMMO classification. The remaining two encounters consisted of multiple species classifications by the eMMO that did not include the species classification made by the iMMO, and an "unidentified dolphin" classification by the iMMO.

Of the 33 marine mammal encounters that occurred during concurrent effort by the eMMOs and the iMMO, 14 were recorded by both observer types (Table 10A). Of the other 19 encounters, i.e., those recorded by only one observer type, the iMMO made fewer encounters than the eMMOs at initial detection distances >500 m. Also, the iMMO was less likely to encounter marine mammals also encountered by eMMOs than the eMMOs were to encounter marine mammals also encountered by the iMMO at initial detection distances >500 m (Table 10B). At initial detection distances ≤500 m, the eMMOs and the iMMO were equally likely to encounter the same marine mammals (Table 10B).

The distribution of bearings to initial detections (for a given encounter) did not differ between the eMMOs and the iMMO (Watson's $U^2_{28,\ 19} = 0.10$, $p > .10$). Also, for the 14 encounters recorded by both MMO types (Table 10A), the differences in initial detection distance and time did not differ significantly between the eMMOs and iMMO. Mean initial detection distances were 0.8 ± SD 1.1 km and

Table 10
Number and conditional probabilities for marine mammal encounters recorded during 43.5 h of concurrent effort by eMMOs and the iMMO. Two of the 14 encounters observed by both the eMMO and the iMMO were excluded from the analyses by distance bins (last two columns) because they were initially detected at distances <500 m by the iMMO and at distances >500 m by the eMMO.

	Initial detection distance		
	All distances	≤ 500 m	> 500 m
A. *Number of encounters recorded by*			
eMMO only	14	4	10
iMMO only	5	4	1
eMMO and iMMO	14	8	4
Total no. of encounters	33	16	15
B. *Conditional probabilities (no. of encounters used in calculation)*			
P(iMMO|eMMO)	0.50 (33)	0.67 (16)	0.29 (15)
P(eMMO|iMMO)	0.74 (33)	0.67 (16)	0.80 (15)

0.5 ± 0.8 km, respectively (1-sided paired $t_{13} = 1.51$, $p = .078$). The eMMOs made initial detections an average of 91.9 s before the iMMO (1-sided paired $t_{13} = -0.59$, $p = .28$).

3.6. Experienced vs. inexperienced PAM

Over the course of the 142.7 h of observation effort during which ePAM and iPAM shifts overlapped, iPAM operators made more detections than ePAM operators, and localized a somewhat larger proportion of those detections (Table 11A). iPAM operators also made more detections (with or without localizations) per encounter than did ePAM operators, and iPAM operators recorded slightly fewer encounters overall (Table 11B).

ePAM and iPAM operators classified roughly the same proportion of marine mammal acoustic detections to species level (ca. 20%; 1-sided Fisher's exact test, $p = .32$; Table 11A). Sperm whales were the only species-level classification assigned by iPAM operators; ePAM operators made single classifications of humpback whale and Risso's dolphin in addition to sperm whales (Table 12). Considering only encounters recorded by both ePAM and iPAM operators, the same classification was reached in 59 of the 84 shared encounters: unidentified dolphin (39); sperm whale (17); blackfish, i.e., pilot whales, killer whales or Risso's dolphins (2); unidentified dolphin and blackfish (1). Of the remaining 25 shared encounters, ePAM and iPAM operators assigned more specific taxonomic ranks in 18 and 5 encounters, respectively. The less-specific taxonomic classifications were primarily "unidentified dolphin".

For the 57 encounters that were localized by both ePAM and iPAM operators, the differences in initial sighting distance and time did not differ significantly between them. Mean initial sighting distances were 1.7 ± 1.6 km and 1.3 ± 1.0 km, for ePAM and iPAM operators respectively (Wilcoxon signed rank test: V = 977.5, $p = .232$). The iPAM operators made initial sightings an average of 197.8 s before the ePAM operators (1-sided paired $t_{56} = 2.41$, $p = .99$). The probability that an encounter recorded by an iPAM operator was also recorded by an ePAM operator was marginally less (71%) than the probability that an encounter recorded by an ePAM operator was also recorded by and iPAM operator (67%; Table 13).

Table 11
Marine mammals detected by ePAM and iPAM operators during 142.7 h of concurrent effort. Encounters consist primarily of repeat detections of the same individual or group of marine mammals; detections were assigned to encounters during post-processing of data.

	Observer type	
	ePAM	iPAM
A. *Number of detections*		
Localized	94	156
Not localized	50	65
Total (proportion of total localized)	144 (0.65)	221 (0.70)
Categorized to species level (proportion of total)	29 (0.20)	39 (0.18)
B. *Number of encounters*		
Localized	81	88
Not localized	44	31
Total	125	119
Mean no. of detections per encounter	1.2	1.9

Table 12
Marine mammals detected and classified by ePAM and iPAM operators during 142.7 h of concurrent effort. Not all detections were localized.

Marine mammal group/species	Number of detections	
	ePAM	iPAM
A.Baleen whale		
Humpback whale	1	0
B.Toothed whales		
Pilot whale spp.	9	0
Blackfish (i.e., pilot whale or killer whale)	9	18
Common dolphin spp.	9	0
Risso's dolphin	1	0
Unidentified dolphin	88	164
Sperm whale	27	39
Totals	143	221
Grand Totals	144	221

4. Discussion

We investigated the detection of marine mammals using three methods: 1) visual, 2) acoustic, and 3) IR imaging. Given the high interest in exploring for oil and gas reserves in the marine environment (e.g., NMFS, 2018), we interpret our results in the context of effectiveness for monitoring and mitigation during seismic surveys.

4.1. How do different marine mammal detection methods perform?

4.1.1. General functioning of the IR imaging system

Our results clearly demonstrate the potential for using a vessel-mounted IR imaging system to detect marine mammals in real-time, in conditions where ocean and air temperatures are both ca. 18 °C. Our results are corroborated by the recent findings of Horton et al. (2017), who made IR detections of humpback whales at a tropical site in Rarotonga, Cook Islands, and a temperate/cold water site in Sitka Sound, Alaska. They observed similar anomalies in radiance from the bodies of the humpback whales and the nearby ocean surface despite a ca. 16 °C difference in ocean surface temperature between their two field sites.

The rotating IR imaging system routinely detected small cetaceans (dolphins and pilot whales) in addition to large whales. IR detections of small cetaceans were made mostly during encounters when dolphins were observed approaching, swimming within ca. hundreds of meters

Table 13
Number and conditional probabilities for marine mammal encounters recorded by ePAM and iPAM operators during 142.7 h of concurrent effort. Only encounters that were localized are included.

A. *Number of encounters* recorded*by*	
ePAM only	41
iPAM only	35
ePAM and iPAM	84
Total no. of encounters	160
B. *Conditional probabilities (no. of encounters used in calculation)*	
P(iPAM|ePAM)	0.67 (160)
P(ePAM|iPAM)	0.71 (160)

of, and bow-riding our research vessel. Dolphins have previously been detected via a handheld binocular IR imaging system (Sagem MATIS; Baldacci et al., 2005), whereas the rotating IR imaging system we used had previously primarily detected large whales (Zitterbart et al., 2013, 2020). The relatively low camera height (7.8 m in this study; ca. 15.5 m in Baldacci et al., 2005) compared to the 26 to 28.5 m camera height used in previous studies with the rotating IR camera facilitated detections closer to the vessel. A minimum detection distance of ca. 90 m was possible when the IR camera was mounted at 28.5 m (unpublished data), due to the vertical field of view of the camera.

That humans were able ***to classify IR detections*** only into broad marine mammal categories points to the utility of this system as a "bell-ringer" for MMOs (Zitterbart et al., 2013) instead of a stand-alone detection and classification system. Currently, this attempt at species-level classification of IR detections is done by humans, and not attempted in the IR imaging design. Classification of IR detections can be done in near real-time if the IR system is constantly monitored by a technician experienced in classifying these images. Although screening out false positives before sending IR alerts to an MMO would be beneficial in reducing distractions caused by false alerts, a further real-time classification of true positive IR detections to the species level would not provide the MMO with much additional advantage in terms of improving mitigation ability.

4.1.2. Real-time IR system use by MMOs while making observations

The greatest challenge we faced in using this system to alert MMOs to the presence of marine mammals was the large number of ***false positive*** detections. Multiple alerts, often caused by birds (but occasionally also caused by detections of marine mammals that repeatedly surfaced near the vessel, i.e., during prolonged encounters with dolphins), were sometimes received within a single minute. During these encounters, aMMOs found the alerting system to be more of a distraction than a help, and once they became overwhelmed by the high rate of alerts, they simply turned the alerting system off. A much lower false positive rate (ca. six per hour) was experienced on average during seven expeditions in the Arctic and Southern oceans, and false positives were attributed primarily to birds (Zitterbart et al., 2013). However, Zitterbart et al. (2013) did occasionally experience false positive rates that exceeded one per minute in the presence of bird flocks. The potential for birds to cause false positive detections highlights the importance of considering the abundance and behavior of non-target species in a study area when planning the deployment of IR imaging systems. For example, during shore-based monitoring of marine mammals via rotating IR camera at Cape Race, NL, Canada, during summer 2016, plunge-diving Northern Gannets (*Morus bassanus*) contributed to such a high false positive rate that additional data screening was required (unpublished data). This was because the splash created when a gannet broke the water's surface mimicked the appearance of a whale blow. If it is not possible to alter survey timing and location to minimize false positives caused by birds, the inclusion of a bird tracking algorithm (see Zitterbart et al., 2020) might help reduce the false positive rate in spite of birds being present in high numbers.

4.1.3. Relative performance of our THA setup compared to THA used during seismic surveys

The comparison of PAM detections made during our study with those made during seismic surveys illustrates some of the challenges with employing "conventional" THA for mitigation purposes. In making these comparisons, it must be noted that we undoubtedly experienced different sound characteristics than those experienced on a large seismic vessel because our research vessel was relatively small, we towed the THA 300 m behind the vessel, and we did not have an active sound source (i.e., airgun array) present.

The encounter rates during our study (ca. 1 encounter per hour, for both ePAM and iPAM; calculated using detection rates in Table 2 and the mean number of detections per encounter, Table 11) were ca. 5.5 times higher than those during a recent seismic program on the Scotian Shelf during May through September (RPS Energy Canada, 2014). During the RPS program, the combined detection rate for the six vessels involved in acoustic monitoring was 0.183 detections per hour. Assuming our PAM encounter rates reflect a higher detection rate because of lower background noise levels, comparisons of the number of PAM detections with MMO and IR detections made during this study likely overestimate the expected relative performance of PAM during a seismic survey.

The performance of our THA in detecting baleen whales appears to be comparable to that of other THAs used for monitoring programs during seismic surveys. The THA that we deployed was capable of detecting baleen whale vocalizations above ca. 500 Hz to 1 kHz, but only when the received signal level of the call was well above the ship engine and cavitation sound levels. Though several species of baleen whales (humpbacks, fin whales, and whales identified as either Balaenopterids or unidentified baleen whales) were confirmed to be vocalizing in the vicinity of our vessel via the deployment of sonobuoys (unpublished data), we made only a single detection of a humpback whale using our THA on 13 August 2017. During a five-month monitoring program for a seismic survey conducted offshore Nova Scotia, conventional THAs were used during the first four months supplemented by an ultralow frequency THA designed specifically to detect blue and fin whales in the last month (RPS Energy Canada, 2014). A single acoustic detection of an unidentified baleen whale was reported during the RPS program. The whale was detected only acoustically by the PAM operator and was not "seen on the low frequency computer" (RPS Energy Canada, 2014). As well, PAM data collected over the course of 76 seismic surveys conducted in UK Continental Shelf (UKCS) waters during 1995 to 2010 resulted in 772 acoustic detections. Only one of these detections was confirmed as a baleen whale, and a second detection "may" have been a minke whale (Stone, 2015b). During the UKCS surveys, the majority of the PAM data were collected using THA deployed behind vessels, though some data were from "stationary platform deployments" (Stone, 2015b).

4.1.4. Detections made during darkness, low visibility due to precipitation, and high sea state

During this survey, marine mammal detections were made in ***darkness*** using both PAM and IR methods (Table 2). IR detection rates were lower in darkness than during daylight (Table 2). In contrast, the same IR system was deployed during seven vessel-based expeditions to the Arctic and Southern oceans, and in those areas the IR system performed better at night (Zitterbart et al., 2013), though direct comparisons are difficult due the stabilization limitations during this study. Any comparison of night vs. day-time detection rates must consider the potential for there to be circadian patterns in behavior of the species encountered, as this will affect their availability for detection. For example, circadian patterns have been documented in sperm whale social behavior at the surface (Watkins et al., 1999), and humpback whale surface feeding behavior (Friedlaender et al., 2009). Similarly, the detection rate for the THA (ePAM and iPAM combined) during this survey was lower at night than during the day. But again, these detection rates could reflect circadian patterns in cetacean vocal behavior (e.g., Baumgartner and Fratantoni, 2008; Simon et al., 2010; Klinck et al., 2012b; Wang et al., 2016).

The poor performance of the IR system in ***rain, fog, and drizzle*** (Table 5A) during this survey is not surprising given the known effects of fog on LWIR transmission loss and detection range (Beier and Gemperlein, 2004; Winchester Jr. and Gimmestad, 1982), and past performance of IR systems used to detect marine mammals during periods of precipitation or fog (Baldacci et al., 2005; Zitterbart et al., 2020). In areas where fog is routinely present, e.g., offshore Newfoundland during a large proportion of the summer period, the use of an IR system will not greatly improve overall marine mammal detection rates.

The relatively poor performance of the IR system in this study in ***sea states greater than Beaufort 4*** (Table 5B) can be attributed to the inability of the gimbal to adequate stabilize the camera. This corresponds with reports by Baldacci et al. (2005) that their IR system (which was mounted on a tripod without stabilization on the deck of their research vessel), was ineffective in sea states >2 or 3. In studies where IR detections were made of marine mammals during Beaufort 5, the camera was mounted either on a much larger and more stable research vessel or on the shore (Zitterbart et al., 2013, 2020). Given that ca. 45% of this survey was conducted in sea states greater than Beaufort 3, and that seismic survey vessels are generally much larger and more stable than the research vessel used in this study, comparisons of the number of IR detections with visual and acoustic detections made during this study probably underestimate the expected relative performance of the IR system in higher sea states when deployed during a seismic survey.

4.1.5. Species detected and classified using different methods

eMMOs were found to detect both toothed and baleen whales, and to classify approximately half of these as species (≥ 55%, Table 7). In comparison, PAM and IR detections resulted in fewer species-level classifications. Approximately 20% of PAM detections were classified to species level; the majority of which were of sperm whales, though classifications of one humpback whale and one Risso's dolphin were also made (Tables 11 and 12). The remainder of PAM detections were classified to broad taxonomic groups, e.g., blackfish (pilot or killer whales), common dolphin spp. (Tables 7 and 12). Four of the 1427 true positive IR detections were classified to species level (i.e., as sperm whales, Table 3). It is possible that the number of species-level classifications may be increased for both PAM and IR detections. PAM classifications may be improved with the use of automatic species classifiers in *PAMGuard* (e.g. ROCCA or other classification algorithms; Oswald et al., 2013), which can be developed when sufficient vocalization data are available for species of interest in the study area. In addition, the use of an IR camera with a higher focal length may facilitate the ability to classify IR video clips to species level. Whether or not classifying marine mammals to species level has any consequence for effective mitigation depends on how mitigation guidelines are written. In countries where mitigation guidelines apply to all marine mammals (e.g., Brazil, Russia, and the UK; summarized in Weir and Dolman, 2007), species identification is not necessary. In countries where mitigation action is taken only for particular species (e.g., Canada; DFO, 2008) or additional mitigation actions apply to species of concern (e.g., New Zealand; DOC, 2013), the ability to classify detections to species level is more critical, and should be considered when selecting detection methods for monitoring.

4.1.6. Suggestions for maximizing marine mammal detections

Our results clearly show that when employed alone, none of the three methods investigated does a particularly good job of detecting marine mammals. MMOs, PAM operators, and the IR system were found to detect only ca. 20–30% of the encounters detected by other methods (Table 6). The consequence of these low detections rates is that seismic mitigation and monitoring programs that employ a single detection method are likely to miss large numbers of the marine mammals that are present.

Our results indicate which marine mammal detection methods can be combined to complement one another in order to maximize the number of marine mammals detected. During periods of darkness, ***PAM and IR*** methods overcome the MMOs limitation to daylight hours, and more detections can be obtained by using both PAM and IR methods concurrently than by either method alone. The THA detected odontocetes almost exclusively, and the IR system detected both small cetaceans and large whales (sperm and baleen whales). Because there was little overlap in the marine mammals detected by these methods when employed concurrently (Table 6), employing both methods at once will result in a greater proportion of marine mammals being detected overall (i.e., fewer missed mammals). For mitigation purposes, reducing the number of missed animals is very important. However, real-time classifications of marine mammals detected using PAM and IR methods will likely be primarily above the species level.

During periods of high sea state and reduced visibility due to precipitation, total number of detections can be increased by using both ***MMOs and PAM*** methods concurrently rather than either method alone; recalling that PAM detections resulted in localizations slightly >50% of the time. The performance of the two methods (in terms of detection rates) followed a similar pattern as sea state increased. However, in the presence of precipitation, PAM resulted in a greater detection rate than MMOs. Precipitation, when occurring, was generally light during the survey, and the performance of PAM during periods of heavy rain would likely be less than what we experienced, due to increased sound from rain. PAM was found to have more detections in common with MMOs than with IR, but in all cases the probability that the same animals would be detected via both methods was <47% (Table 6). Given that PAM localizations were made at mean distances >1.0 km (i.e., beyond the commonly used 500 m safety zone), the utility in using a THA in a mitigation setting may be that in some jurisdictions, similar to the IR system, it can function as a "bell-ringer" to alert observers to the presence of marine mammals in the general area.

Overlap in detections made via visual and acoustic methods has also been investigated using data collected during seismic surveys conducted in UKCS waters between 1995 and 2010 (Stone, 2015b). It was found that 52% of detections were made only by MMOs, 20% of detections were made only using PAM, and the remaining 28% of detections were made by both MMOs and PAM. The study illustrated that greater numbers of marine mammals can be detected overall when more than one detection method is employed.

Our experimental protocol required that MMOs and PAM operators make detections independently of one another. However, more effective mitigation can be achieved if detections are shared in near real-time across monitoring methods. This can make it possible, for example, for some visual sightings to have their classification confirmed acoustically, and for some acoustic detections to be classified to the species level and geo-located (e.g., resolving the mirror-image ambiguity). The relatively high proportion (ca. 53%) of acoustic detections classified to species level during seismic surveys in UKCS waters was possible because of visual confirmation (Stone, 2015b).

During periods of good visibility, either the IR or PAM system could be used to enhance the number of detections made by MMOs. The probability that the same animals were detected by two methods did not exceed 47% (Table 6), leaving room to increase the total number of detections (and the proportion of the mammals present that are detected) by employing two methods at once. However, the potential increase in employing the IR system in a mitigation setting is currently hampered by our inability to quickly screen out false alerts from the automatic IR detections delivered to MMOs in real-time. This is evident in the marginally lower detection rate for the aMMO compared to the eMMO (Table 2), the relatively large probability that marine mammals will be detected by both aMMO and eMMO concurrently (Table 8B), and by IR alerts being associated with a marine mammal detection ca. 21% of the time (Table 4).

In general, the potential increase in detections that may result from assistance by the IR system is likely underestimated using results from our study. We expect that additional true positive detections of marine mammals would have been made by the IR system had the gimbal been able to stabilize the IR camera during the higher sea states. Assuming an estimate of 50% gimbal stall time, twice as many IR detections might have been made from a larger and more stable vessel. As well, mounting the IR camera in a higher location on the vessel, as has been done previously (Zitterbart et al., 2013), likely would also have resulted in higher detection rates because the camera FOV would be less obstructed by vessel infrastructure, and the detection range of the camera would be greater with increased height.

Employing complementary detection methods simultaneously can increase detection performance overall (e.g., DFO, 2015; Verfuss et al., 2018). In fact, Verfuss et al. (2018) suggest the use of a modelling framework to explore which combinations of methods, in addition to consideration of target species' behavior, should be used to develop better monitoring strategies and regulations. Keeping in mind the caveats mentioned above, the data collected in this survey could be useful in such a modelling effort.

4.2. How does experience level affect MMO and PAM operator performance?

4.2.1. Influence of MMO experience level

Our results suggest that iMMOs may be less effective at employing mitigation actions for marine mammals during seismic surveys than eMMOs. Compared to the eMMOs, the iMMO detected fewer marine mammals (Tables 9 and 10). As well, the iMMO may potentially allow marine mammals to approach the sound source more closely than eMMOs. However, this supposition is based on differences in initial sighting distance and time for the eMMOs vs. the iMMO which were not found to be statistically significant. The iMMO was also less likely to classify marine mammals to species level than the eMMOs, suggesting that iMMOs will be less effective at employing mitigation actions which are prescribed only for specific marine mammals. For example, in Atlantic Canada, "target" species typically include the blue, North Atlantic right (*Eubalaena glacialis*), and Scotian Shelf population of northern bottlenose (*Hyperoodon ampullatus*) whales (DFO, 2008). Mitigation action is taken when MMOs positively identify one of these species and determine that it has or is about to enter the safety zone. However, in cases where mitigation guidelines actions apply to all cetaceans (e.g., JNCC, 2017), the ability of MMOs to classify marine mammals to species level is not essential.

Our results are corroborated by an analysis of sighting data from 1121 seismic surveys within the UKCS between 1995 and 2010. Stone (2015b) found that dedicated MMOs with relevant marine mammal experience prior to becoming an MMO had better detection skills than those without prior experience. As well, sighting rates for experienced MMOs were 3 x higher in all weather, and 2.5 x higher in good weather, compared to inexperienced MMOs. Experienced MMOs were also found to detect animals at greater distances (approximately 1.5 km vs. 1 km, in all or good weather) than inexperienced MMOs (Stone, 2015b).

4.2.2. Influence of PAM operator experience level

We interpret many of the differences in iPAM and ePAM operator performance observed during this study as reflecting a difference in approach to detection taken by the two observer types, as opposed to differences in their capabilities. This difference in approach became obvious when the data were analyzed. We characterize the approach taken by ePAM operators as being conservative. ePAM operators made fewer detections per encounter (Table 11), and waited until marine mammals were abeam of the vessel to localize, which influenced both the distance to, and timing of, detections. In contrast, iPAM operators were relatively quick to record detections, and generally estimated locations using fewer bearings.

The results of this study suggest that ePAM and iPAM operators are comparable in detecting vocalizing marine mammals and classifying them to species level (Table 11A). Similar results were obtained by Stone (2015b) in their analysis of acoustic detections made during seismic surveys within the UKCS between 1995 and 2010. They found no apparent correlation between the number of acoustic detections made and experience level of PAM operators. They also found that of the 772 acoustic detections made, many were classified as unidentified dolphins or cetaceans; and noted that though a number of the detections were classified to species level, this was often the result of visual confirmation (i.e., MMO sightings). In this study, both ePAM and iPAM operators classified most detections as combined species groups (Table 12). Very few species were classified using PAM during our study compared to the UKCS study, though we specifically instructed MMOs and PAM operators to work independently of one another, eliminating the opportunity for visual verification. In our study, both ePAM and iPAM operators readily classified vocalizations made by sperm whales; however, more "challenging" species classifications were made only by ePAM operators (Table 12). The consequence of not classifying a marine mammal to species level depends on how mitigation guidelines are written. For example, JNCC guidelines (2017) apply to all cetaceans, and Canadian guidelines (DFO, 2008) are written such that all "non-identified" cetaceans must be assumed to be target species for which mitigation action is taken. Both examples imply that having PAM operators capable of classifying acoustic detections to species level is not essential for effective mitigation to be employed.

In this study, MMO detection performance and the approach taken to making detections by PAM operators differed with experience level. These differences highlight the importance of having properly trained and experienced field personnel for marine mammal monitoring and mitigation duties during seismic surveys. Not only do field personnel need to possess appropriate skills and knowledge, but they must also be trained to consistently make detections following the same protocol. The importance of having properly trained and experienced personnel is made clear in some mitigation guidelines that specify criteria for an MMO or PAM operator to be considered "qualified" (e.g., JNCC, 2017; NMFS, 2018).

4.3. Study caveats and considerations for future research

It should be noted that the *Leeway Odyssey* is relatively small in comparison with most commercial seismic vessels, the largest of which are currently ca. 100 m in length and 70 m in width (e.g. RV *Ramform Hyperion*). The relatively small size of the *Leeway Odyssey* affected maximum platform heights and the extent of roll and pitch, as well as producing dominant sound energy at relatively higher frequency bands than a larger seismic ship would have produced. These aspects directly influence the performance of the specific detection methods used, and hence affect our results. Our primary recommendation is that future comparisons of detection methods, when the intended application is for monitoring purposes during seismic surveys, be made from aboard seismic survey vessels with and without airguns operating. This will ensure that a stable and appropriately high platform is available for the IR camera, and that PAM detections will be made in the appropriate acoustic setting, i.e., with airgun pulses.

We acknowledge several caveats with our dataset. The lack of distance estimates for the IR detections prevented us from calculating detection functions for the IR system, which would have allowed for a comparison of range detection between methods. Ensuring that future studies provide a stable platform for the IR system will avoid this issue. Another caveat with our study is the lack of data that could be used to ground truth the detection methods. As with other surveys of marine mammals, we do not know how many were present in our study area and are therefore limited to relative comparisons of methods. Along the same lines, marine mammal encounters were defined subjectively by analysts during post-processing of the data. Despite the challenges we experienced, this project has advanced our knowledge of visual, acoustic, and IR imaging methods to detect marine mammals at sea.

4.4. Summary and conclusions.

1. Our results illustrate that each of the three marine mammal detection methods we used perform rather poorly in isolation and suggest that detection performance can be improved when these different methods are employed concurrently, and detections are shared in near real-time across methods. Furthermore, our results showed that PAM and IR methods worked effectively during darkness, that PAM

and visual methods complemented each other during periods of high sea state and low visibility due to precipitation (including fog), and that IR methods can enhance visual methods during periods of good visibility. Employing PAM and visual methods during periods of good visibility also resulted in more detections than if only visual methods were used.

2. The types of marine mammals detected, and the extent to which they were classified to the species level, varied depending on which detection methods were used. MMOs and the IR system effectively detected both baleen and toothed whales at the water's surface, though species were only reliably classified by MMOs. Most PAM detections were of toothed whales, and were classified to the level of broad taxonomic groups (e.g., pilot whale spp., unidentified dolphin, unidentified dolphin or beaked whale).
3. The vessel-mounted IR camera system could detect marine mammals in the thermal regime of Atlantic Canada during summer. However, the IR camera system resulted in a very high number of false positives (84.5%), which was mostly attributable to the detection of seabirds. As such, this system requires further refinement so that the delivery of IR alerts to MMOs in real-time can be effectively used as a monitoring tool. As well, the IR camera must be adequately stabilized, and consideration must be given the height above water at which the camera is mounted.
4. Experience level seemingly influenced MMO detection performance in a several ways. The iMMO effectively monitored less of the viewable area around the vessel, detected fewer marine mammals, and was less likely to classify these marine mammals to species level, relative to eMMOs. The iMMO was also generally slower to detect marine mammals, and made initial sightings of marine mammals when they were closer to the vessel, relative to the eMMOs. These findings suggest that the implementation of mitigation measures related to minimizing the amount of sound exposure (i.e., from an airgun array or other sound source) may be less effective when monitoring is conducted by MMOs that are inexperienced.
5. Detection of marine mammals via PAM, for mitigation purposes, appears to be primarily influenced by hardware and software (as opposed to level of PAM operator training and experience). As well, ensuring that PAM operators are experienced and familiar with vocalizations of marine mammals likely to be encountered in the study area, and have had adequate hands-on experience making detections prior to monitoring for mitigation purposes, should improve the consistency and quality of PAM detections made.

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CRediT authorship contribution statement

Heather R. Smith: Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft, Project administration, Funding acquisition.**Daniel P. Zitterbart:**Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing - original draft, Funding acquisition.**Thomas F. Norris:**Methodology, Formal analysis, Data curation, Writing - review & editing.**Michael Flau:**Software, Investigation, Data curation, Writing - review & editing.**Elizabeth L. Ferguson:**Methodology, Formal analysis, Data curation, Writing - review & editing.**Colin G. Jones:**Investigation, Data curation, Formal analysis, Writing - review & editing.**Olaf Boebel:**Conceptualization, Writing - review & editing, Funding acquisition.**Valerie D. Moulton:**Conceptualization, Writing - review & editing, Supervision, Funding acquisition.

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Declaration of competing interest

- HRS, CGJ, and VDM are employed by LGL Limited, environmental research associates, an independent consulting company that conducts baseline research studies and studies to evaluate impacts of human activities on marine mammals, and supplies marine mammal observers to conduct monitoring programs during seismic surveys and other industrial activities in the marine environment.
- DPZ and OB declare competing financial interests: 1) Patent US8941728B2, DE102011114084B4: A method for automatic real-time marine mammal detection. The patent describes the ideas basic to the automatic whale detection software as used to acquire and process the data presented in this paper (http://www.freepatentsonline.com/y2013/0070079.html). 2) Licensing of the Tashtego automatic whale detection software to the manufacturer of IR sensor. The authors confirm that these competing financial interests do not alter their adherence to good scientific practice.
- TFN and ELF are employed by Bio-Waves Inc., a small business that conducts bioacoustics and marine mammal research, including studies to evaluate impacts of human activities on marine mammals. Our clients include large governmental organizations such as the National Oceanic and Atmospheric Administration, the U.S. Navy as well as large industry associations such as the International Association of Oil and Gas Producers - Sound and Marine Life Joint Industry Programme. We often partner with both small and large private companies, non-profit organizations, and academic institutions to conduct our work.

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