# Review of Night Vision Technologies for Detecting Cetaceans from a Vessel at Sea

## Produced for South Fork Wind

07 January 2021

**Prepared for:**

**Ørsted, North America**
**399 Boylston St., 12th Floor**
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**Citation**

Smultea Environmental Sciences, LLC (Smultea Sciences). 2021. Review of Night Vision Technologies for Detecting Cetaceans from a Vessel at Sea. Prepared by M.A. Smultea, G. Silber, P. Donlan, D. Fertl, and D. Steckler. Prepared for Ørsted North America, 399 Boylston St., 12th Floor, Boston, MA 02116. 7 January 2021.

# Table of Contents

# List of Figures



# List of Tables

# Acronyms, Initialisms, and Abbreviations

| | |
|---|---|
| A/D | analog to digital |
| AI | artificial intelligence |
| AIMMMS | automatic marine mammal mitigation system |
| ASL | above mean sea level |
| Bft | Beaufort sea state |
| BOEM | Bureau of Ocean Energy Management |
| C | Celsius |
| CCD | charge-coupled device |
| DZ | dead zone |
| FLIR | Forward-Looking Infrared camera |
| FOV | field of view |
| FPA | focal plane array |
| G&G | geophysical and geotechnical survey |
| GP | geophysical |
| GT | geotechnical |
| HD | high definition |
| hh | handheld |
| Hz | Hertz |
| ICAO | International Civil Aviation Organization |
| IR | infrared |
| km | kilometer(s) |
| LW | long wave |
| m | meter(s) |
| mm | millimeter(s) |
| MMO | marine mammal observer |
| MSL | mean sea level |
| MW | medium wave |
| NARW | North Atlantic right whale |
| nm | nanometer |
| NMFS | National Marine Fisheries Service |
| NOAA | National Oceanic and Atmospheric Administration |
| NVD | night vision device |
| PAM | passive acoustic monitoring |
| pdf | perpendicular detection function |
| PSO | Protected Species Observer |
| RADES | Real-time Automated Distance Estimation at Sea |
| sec | second(s) |
| SR | scan range |
| USD | U.S. dollars |
| WGWAP | Western Gray Whale Advisory Panel |

# 1 Abstract

We identified, reviewed, and evaluated available information on the effectiveness of infrared and light-enhancing technologies/systems for detecting marine mammals from at-sea platforms during darkness and in low-light conditions. We focused our effort on cetacean detections at distances of 1-2+ kilometers (km), particularly endangered whales. This paper provides supporting documentation regarding the use and efficacy of night vision devices (NVD) for mitigation and monitoring during various offshore wind energy development activities in the U.S. North Atlantic, including construction. We assess existing technologies, summarize literature review results, identify sources (i.e., manufacturers) of individual devices, and provide information on relative costs of acquiring and properly using such devices (as available). With the exception of a few high-end devices, most of these technologies have not been thoroughly or systematically examined in the field to reliably detect whales, dolphins, or pinnipeds at sea. Most such information, therefore, is based largely on theoretical modeling and laboratory testing.

Efficacy of handheld, light-enhancing device performance is generally limited to distances of <200 meters (m) for cetaceans and <100 m for pinnipeds and sea turtles. Mounted, uncooled thermal infrared (IR) devices have been reported and modeled to detect whales and other cetaceans at distances of up to several kilometers, but systematic field trials to date are limited; thus, detection probabilities for these technologies as a function of distance are largely untested. Cooled IR sensors/systems, including those with proven, automated image-recognition software capabilities, have performed well (>90% detection probability at 1.5-2+ km) in systematic field trials from large and/or stable platforms, with detections reported to 8+ km. However, such custom-built systems must be pre-ordered (~1 year notice).

A concurrent 360° view is critical to maximize cetacean detection probability around a stationary sound source (e.g., a pile driving vessel platform). This can be accomplished within 1.5-2+ km with either a high-end IR system and/or multiple mounted IR cameras whose field of views summarily cover 360°. Optimal selection of IR optical features is dependent on numerous factors including mitigation distances, species of interest, typical environmental conditions, and operational considerations. For optimal detection performance within several km, proper placement is essential. For optimal performance, IR systems with high-resolution optics should be mounted at heights of at least 15-20 m above the water surface on large, stable platforms with unobstructed views.

There remains a clear need for systematic studies with sufficient data collection to empirically test theoretical model performance and draw comparisons between devices across a wide range of conditions. Such studies would involve repeated trials under various conditions to objectively assess the capabilities of each system to reliably and consistently detect marine mammals during darkness/low-light conditions at various distances.

# 2 Introduction

Marine mammals spend most of their time submerged. Therefore, reliably and consistently detecting marine mammals at sea has long been a vexing problem. This is the case for study and observation of marine mammal occurrence, movements, and behavior, but can also complicate or hamper routine industrial activities such as marine oil/gas exploration/development and offshore renewable energy facility siting surveys, construction and operations. Some rapidly developing and emerging technologies such as passive acoustic monitoring (PAM) and improvements in instrument optics have improved this situation, but there remains a need to improve detection capabilities, particularly in adverse conditions such as periods of low-light/darkness. Means to detect marine mammal occurrence are needed for these activities to continue in all conditions, e.g., adverse weather and low-light conditions.

## *2.1 Purpose*

The purpose of this white paper is to provide a summary review to support the use and efficacy of thermal IR devices for marine mammal mitigation and monitoring during various offshore wind development activities, including construction. Specifically, this paper provides supporting documentation for Ørsted to both the National Marine Fisheries Service (NMFS) and the Bureau of Ocean Energy Management (BOEM). Of particular focus is to identify, review, evaluate, and discuss IR technologies/systems considered most effective at detecting large, endangered whales that may occur within 2 km of an active pile driving sound source during darkness/low-light conditions. Species of particular focus are the North Atlantic right whale (NARW), as well as humpback (the most commonly detected endangered whale in the region) and fin whales. The 2-km radius represents the anticipated Level-A isopleth for marine mammal mitigation and monitoring during pile driving activities associated with offshore windfarm construction. As such, this paper focuses on IR devices/systems considered most effective at detecting large whales within this distance based on a review of available information (e.g., published literature, gray literature, and personal communications with experts).

This paper also reviews what is known about the effectiveness of various IR devices and NVDs for detecting cetaceans (e.g., delphinids, porpoises, and whales) within various distances. Evaluated distance categories range from 200 to >2000 m from an observation height of approximately 10-20 m above mean sea level (MSL). These conditions represent those anticipated aboard vessels from which Protected Species Observers (PSOs) are expected to observe (e.g., jack-up rig, survey vessel, barge) during offshore wind construction, operations, and maintenance activities. Note that during pile driving, PSOs are expected to observe primarily from a stationary vessel platform. This review focuses, as feasible, on the northwestern mid-Atlantic Ocean (Massachusetts to South Carolina) with consideration given to ambient temperatures and other environmental influences on detection effectiveness.

## *2.2 General Approach*

Detection of marine mammals at sea presents challenges. For the reasons identified above, conducting certain offshore industrial activities is predicated on determining the presence/absence of marine mammals in prescribed areas. However, means to do so reliably can be expensive and logistically complicated and can be hampered by meteorological and oceanographic conditions.

The availability and effectiveness of various technologies and software systems to improve sighting/detection rates during darkness and low-light conditions has been advancing rapidly. Among these are various thermal IR, heat-sensing, and vision/light-enhancing devices. However, with the exception of a few high-end devices, most of these technologies have not been thoroughly or systematically examined in the field to reliably detect wild whales and dolphins at sea; thus, performance metrics are typically based on theoretical models and trials in terrestrial settings which are very different from at-sea conditions.

To explore what is known (at the time of the writing of this paper) about the feasibility and effectiveness of using such devices in practical, at-sea conditions, Smultea Environmental Sciences (Smultea Sciences) herein conducted a literature review of various thermal and low-light vision/detection devices within four standard distances regularly or anticipated to be employed in monitoring/mitigation requirements (<200 m, 201-500 m, 501-2000 m, and >2000 m). This review includes a summary and assessment of existing technologies, identifies sources (i.e., manufacturers) of individual devices, and provides information on relative costs of acquiring, using, and maintaining such devices (as available). Evaluations of individual devices currently available for use for this purpose are also provided.

This paper starts with a general background review of the two primary technologies examined (IR/thermal and low-lighting imaging). This is followed by a review of literature, a description of the process applied to identify relevant device specifications, and ends with a comparative discussion of select, relevant device features. Appendices are provided at the end of the document after the Literature Cited.

## *2.3 Monitoring and Mitigation Context: Observation Platform Height*

Before reviewing available night vision technology, it is important to understand extrinsic and intrinsic factors and limitations affecting mitigation and monitoring approaches for marine mammals, particularly relative to offshore wind development and operational activities in the U.S. North Atlantic. Observation height above water is a critical factor affecting how far a PSO or mounted camera device can detect an animal. As platform height increases, so does distance to the horizon concurrent with the ability to detect marine mammals at distance using surface methods. For example, at 1.5 m above mean sea level (ASL), the distance to the horizon (incorporating curvature of the earth) is estimated to be 4.4 km on a clear day. In comparison, distance to the horizon from a high cliff at elevation 100 m above ASL is 35.7 km, while from an aircraft flying at 500 m, the horizon is visible out to a distance of 79.9 km. **Error! Reference source not found.** illustrates the calculated differences in distance to the horizon for various anticipated observation heights during construction phases and includes some actual eye heights from vessels used by Ørsted and Smultea Sciences PSOs during geophysical (GP) and geotechnical (GT; jointly referred to as G&G) surveys. The table also includes other lower and higher observation platform distances to the horizon for comparative purposes.

**Table 1. Distance to the horizon based on observation height above mean sea level (ASL), including from various vessel platforms used by Ørsted for G&G surveys based on average observer eye height (EH; 1.65 m) ASL.**

| Horizon Distance | | | Vessel Name and Protected Species Observer (PSO) Location (as Applicable) |
|---|---|---|---|
| Observation Height ASL (ft) | Observation Height ASL (m) | Distance to Horizon (m)[1] | |
| 5.0 | 1.5 | 4,406 | |
| 10.0 | 3.0 | 6,231 | |
| 15 | 4.6 | 7,632 | |
| 20 | 6.1 | 8,813 | |
| 25 | 7.6 | 9,853 | |
| 26.4 | 8.0 | 10,048 | *Explorer* lower deck |
| 30 | 9.1 | 10,793 | |
| 33.1 | 10.1 | 11,320 | *Royal* bridge outside |
| 36.3 | 11.1 | 11,823 | *Explorer* bridge; *Brazos* baseline (has an additional 1.5-5 m lift capabilities); *Royal* bridge |
| 36.9 | 11.3 | 11,987 | *Searcher* bridge |
| 39.4 | 12.0 | 12,306 | *Highland Eagle* outside bridge deck; *Regulus* bridge |
| 40 | 12.2 | 12,463 | |
| 40.7 | 12.4 | 12,618 | *Highland Eagle* bridge |
| 45.9 | 14.0 | 13,365 | *Highland Eagle* flying bridge |
| 47.67 | 14.5 | 13,510 | *Explorer* tweendeck |
| 50 | 15.2 | 13,934 | |
| 55.1 | 16.8 | 14,614 | *Explorer* helideck |
| 60 | 18.3 | 15,264 | |
| 62.17 | 19.9 | 15,516 | *Brazos* (when boat lifted) |
| 65 | 19.8 | 15,887 | |
| 70 | 21.3 | 16,487 | |

[1]Distance to horizon calculated using Mysticetus System software which includes correction for curvature of the earth. Distances to horizon are provided for heights at 5-meter intervals and at heights specific to G&G vessel PSO eye height, in ascending order of height ASL.

Practical or effective sighting ranges are dramatically lower than computed distance to horizon due to extrinsic factors (e.g., humidity, swell, Beaufort [Bft] sea state). Figure 1**Error! Reference source not found.** illustrates how the effective detection distance (i.e., detection function) of an IR vision device for detecting whales increases with increasing height ASL based on empirical data collected from three shore-based locations (Zitterbart et al. 2020a). Figure 2 and **Error! Reference source not found.** further illustrate the relationship between effective detection distance and observation platform height based on results of studies using mounted thermal devices to detect whales (Zitterbart et al. 2020a,b).

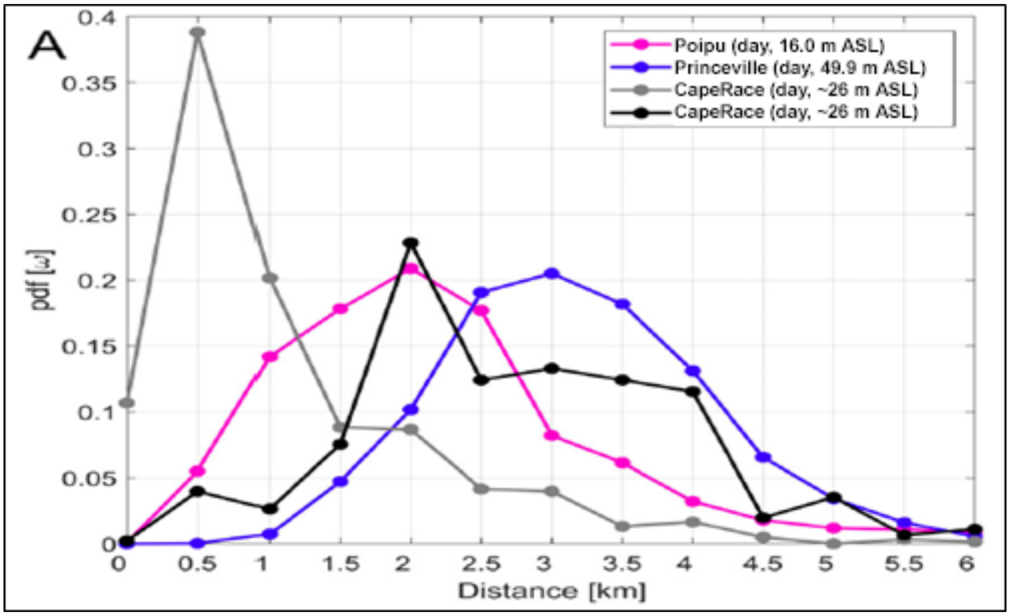


**Figure 1. Perpendicular detection functions (pdf) for the automatic detection algorithm using thermal imaging data acquired by a rotating line scanner (FIRST-Navy, Rhenimetall Defence Electronics, Bremen, Germany) at three different shore-based observation platform locations featuring different sensor heights and environmental regimes.** All data were obtained during daylight with the exception of the Cape Race site where data were also obtained during darkness. Poipu = Southern Kauai, Hawaii; Princeville = Northeast Kauai, Hawaii; Cape Race = Cape Race, Newfoundland, Canada. (Source: Zitterbart et al. 2020a). Results demonstrate that the lower ASL stations were associated with a closer sighting peak. Note that results for the Cape Race day are an artifact of diurnal differences in humpback distribution associated with prey feeding closer to shore during the day.

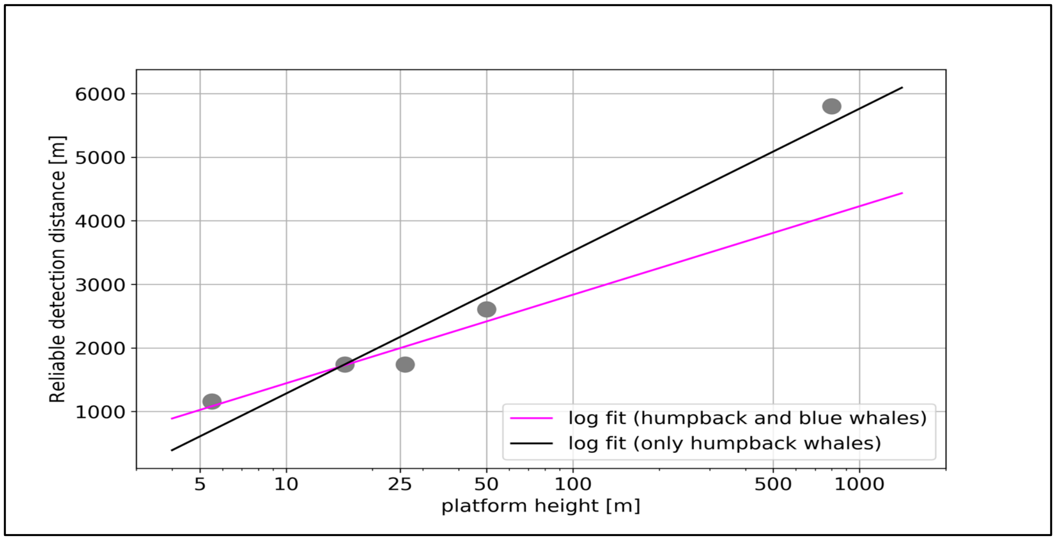


**Figure 2. Logarithmic fits of approximate reliable detection distances by platform height for thermal imaging data obtained on humpback and blue whale blows. (Source: Zitterbart et al. 2020b).**

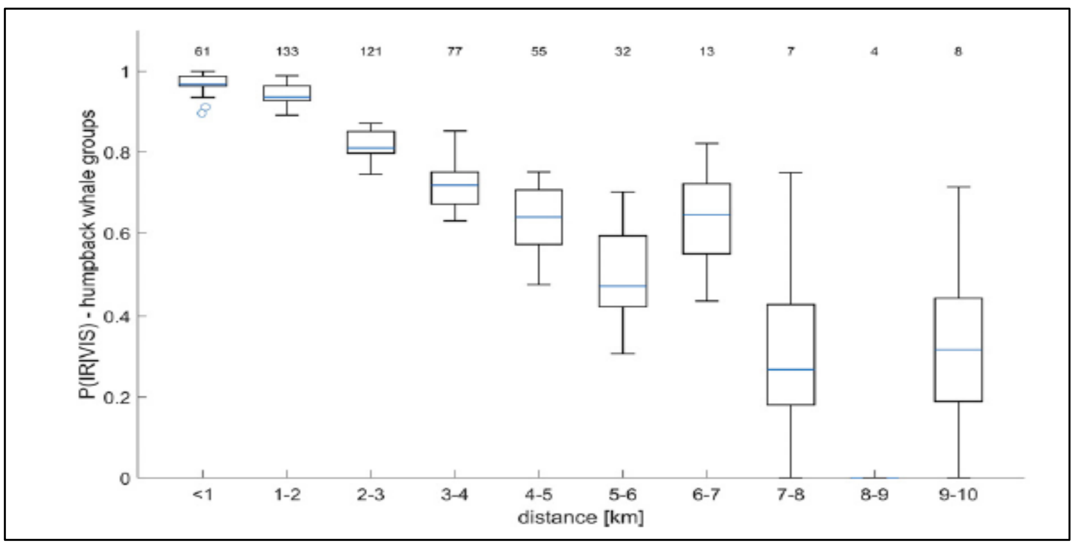


**Figure 3. Probability of perception (P [IR/VIS]) for detection of humpback whales relative to distance to the observer at a shore station during use of a thermal imager located at 51.3 m ASL on North Stradbroke Island, Queensland, Australia.** Error bars depict standard deviations obtained via bootstrapping. Numbers along top of graph indicate the number of encounters in each bin. Probability of Perception (i.e., Thermal Perceptibility) defined as how well a whale cue (e.g,. blow, splash, back, breach) in the thermal infrared video stream is perceived by an informed human observer. (Source: Zitterbart et al. 2020a). Results indicate that over 90% of whale cues were perceived using the thermal camera system within a distance of 2 km.

The number of vessels in the U.S. North Atlantic suitable to conduct G&G investigations associated with offshore wind siting surveys is limited, and those suited to conduct offshore wind construction involving installation of piles are even further limited. Typical eye height ASL for PSOs during G&G surveys conducted by Ørsted in the U.S. North Atlantic for offshore wind development since 2016 have ranged from approximately 1–2 m for small vessels conducting nearshore/inland underwater cable route surveys to approximately 8–20 m for larger marine survey ships (this includes deck height plus average PSO eye height as shown in Table 1). Lift boats and barges stationed in place are expected to be used for the construction phases of offshore wind construction for activities such as pile driving. These vessels are anticipated to range in PSO eye heights of approximately 12–20 m ASL based on vessels known to be purposed for such activity in the region. Notably, lift boat deck heights can be increased or decreased, depending on the activity at hand, resulting in typical changes in PSO eye height by at least several meters (see Table 1 – *Brazos*).

It is important to note that most data available on object detection probability, and thus detection functions for thermal cameras, are based on theoretical models applied to terrestrial environments, foremost for military purposes, but also for rescuing persons at sea. However, a number of empirical studies have been conducted specifically for assessing detection effectiveness and detection probability of marine mammals, primarily cetaceans and foremost whales, from elevated shore-based platforms and vessels at sea. Systematic studies assessing the effectiveness of thermal devices for detecting cetaceans from vessels are particularly limited. The latter studies have involved primarily high-end thermal camera devices. These handful of studies indicate that whales and dolphins can be detected 5-10+ km away under ideal viewing conditions (e.g., flat seas, no glare, low Bft sea state, little to no swells, clear skies/no rain or fog). However, reliable (>90% probability) and consistent detection is limited to closer distances, results of which are affected by observation height ASL as well as intrinsic and extrinsic factors. Results and theoretical modeling further indicate that some thermal IR devices are capable of high probability detection of whale blows out to 1.5-2+ km from observation platform heights of 15-20+ m. Measured effective range comes with strong camera configuration dependencies.

With respect to this paper, studies indicate that to detect whale blows with high reliability and probability, minimum preferred observation platform height is approximately 15-20 m (e.g., Zitterbart et al. 2020a,b). This is feasible for mounted thermal IR devices given the combination of vessels available for such work in the U.S. North Atlantic and the ability for many thermal devices to be mounted on poles and high structures on vessels. Results of studies reviewed herein include observation platform height wherever possible, given the importance of this factor when considering detection distance effectiveness.

## *2.4 Availability and Perception Bias Considerations and Context*

The purpose of this paper is to evaluate the effectiveness of using night vision technology for detecting marine mammals during darkness and lowlight conditions within and near anticipated mitigation distances associated with underwater noise produced during offshore wind construction, operations, and maintenance. An important related consideration is the concept of availability and perception bias with respect to probability of detection of protected species. Mitigation and monitoring results summarized in technical reports to meet NMFS and BOEM requirements for offshore wind G&G surveys have compared detection rates (number of detections per hour of observation effort) of protected species based on PSO use of various visual (and PAM) detection methods during daylight and darkness (e.g., Smultea et al. 2017, 2018, 2019, 2020). Results indicate that detection rates are generally lower during darkness compared to daylight. Methods for visual detection during darkness included the naked eye in areas lighted by a vessel's operating lights, handheld light-enhancing NVDs, handheld IR binoculars/monocular, and uncooled mounted thermal IR camera systems.

Report results indicate that during darkness, the first three visual methods are most effective within 200 m of the observer, with mounted thermal cameras outperforming the other three methods at distances of approximately 200-500+ m (summarized in Smultea et al. 2019). Under good observation conditions (low humidity, typically Beaufort <4), PSOs have detected and identified large whale blows and groups of delphinids during darkness at distances up to approximately 1-2 km with mounted thermal camera systems, as documented by still and video image recordings (e.g., Smultea et al. 2019). These nighttime detections have included multiple sightings of probable or confirmed North Atlantic right whales identified by the species' distinctive v-shaped blow and/or a lack of dorsal fin.

Detection rates presented in the technical reports cannot be directly compared between daylight and darkness, attributable to two primary factors:

1. The area *within view* of PSOs is significantly larger during daylight than darkness, and extends well beyond the required mitigation distances of up to approximately 200 m for G&G activities with the exception of 500 m for the North Atlantic right whale. Thus, during darkness, the 'covered' area was spatially significantly smaller resulting in a reduced likelihood of detection. A more equivalent approach would be to compare detection rates within 200 and 500 m of the PSOs during daylight versus darkness.

2. The mounting configuration of the two uncooled IR cameras on the vessel combined with camera optical specification settings/limitations (e.g., a limited optical field of view [FOV]) did not provide full *concurrent* 360˚ view coverage (unlike for visual PSOs during daylight) due to camera panning. This resulted in viewing gaps that inherently increased the likelihood of missing some detections during darkness. For example, a humpback whale blow is estimated to be visible for capture by a thermal detection device for an average of approximately 4-5 seconds (sec).[1] Adding

[1] As an example: Hypothetically, a single IR camera with a 40˚ FOV panning at 3˚ per sec will have only 'seen' a total of 55˚ radial of the total 360˚ view (based on 40˚ FOV + [5 sec x 3˚/sec]); this leaves 305˚ of the total 360˚ 'uncovered', resulting in a high probability of missing the blow event during the blow's active detection window of 5 sec. Recent IR camera deployments for G&G surveys in the U.S. Atlantic have been approved for two concurrently-operating IR cameras, which reduces the single-camera coverage gap of 305˚ in the this example to 250˚.

cameras improves the probability of detection by increasing concurrent coverage of the larger area/view.

Nonetheless, monitoring for marine mammal presence at the water surface is inherently biased and under-representative of the actual numbers of animals within a given area (Marsh and Sinclair 1989; Barlow 1999). This is due to two documented categories of missed animals during visual observations, regardless of daylight or darkness: perception bias and availability bias. Perception bias consists of those animals that are potentially visible to observers but are not seen; availability bias consists of those animals that are not available to observers because they are concealed (e.g., below the water surface, poor sighting conditions such as low-light; Marsh and Sinclair 1989; Barlow 1999).

Monitoring for cetaceans with thermal imaging camera systems is presumed to be characterized by the same inherent availability and perception bias limitations as those experienced by visual PSOs in a given context. Perception bias can be reduced by increasing the number of PSOs on visual watch or by increasing the number or coverage (in terms of FOV) of thermal cameras, both which serve to reduce/narrow the range of area being monitored; this allows more focus on a given area, improving detection probability. Recent studies have found that under some conditions, IR camera systems (including with image recognition software) outperform experienced visual PSOs (Zitterbart 2020a). In the latter case, the particular IR camera is capable of maintaining a full 360°view of the observation area, while the on-duty PSO(s) alternates scanning between the naked eye and binoculars and cannot keep their eyes on the full area covered by the IR camera optics. In addition, PSOs are susceptible to fatigue and distraction which has been shown to contribute to missed detections, while cameras are not. For example, visual PSOs missed whale blows identified by the IR camera system that were later confirmed by a PSO reviewing camera video. Numerous studies report that use of thermal cameras remotely monitored by PSOs, especially when audible alarms alert the PSOs of marine mammal presence, can complement and increase overall detection rates (e.g., Smith et al. 2020; Zitterbart et al. 2013, 2020a). The exception being cases where excessive false positives have falsely distracted PSOs (e.g., in areas with many birds, etc.; e.g., Smith et al. 2020).

Duration of surfacing is expected to impact detection rates similarly for visual PSOs and IR cameras. In both cases, missed animals are related to perception and availability bias, not system capability. Hain et al. (1999) noted that for whales, diving behavior and time submerged are the principal factors affecting availability for visual detection of whales. For large whales, the time that an animal or its blow is visible to an observer has been measured to range from 2.7 sec for sperm whales to 5.1 sec for blue whales (Doi 1974 in Barlow 1999).

In summary, evidence indicates that perception and availability bias can be minimized and thus probability of detection maximized during darkness/low-light conditions by using an IR camera system with advanced optics that maintains a concurrent 360° view of the area of interest. Based on available data, this is best optimized by complimenting visual PSOs with this type of IR camera system, as exemplified in following sections.

# 3 Technology Overview

Two primary types of night vision technologies have been used for monitoring marine mammals at sea and are the focus of this review: light-enhancing imaging and IR technologies. Though unaided eye is used for marine mammal detection during darkness at times when vessel operating lights illuminate nearby waters, this method is not evaluated here. A literature review of the use of near-infrared and short-wave illumination for detecting marine mammals at sea was conducted. However, no known examples of short-wave illumination technology were found to be in use for this purpose, thus no further discussion of these types is provided.

Information on how light-enhancing imaging and IR technologies work is provided in the sections that follow. Our review of devices is based on manufacturer data as well as written and spoken performance reviews reported by manufacturers, field users, and research on this topic.

## *3.1 Infrared (IR)/Thermal*

IR/thermal sensors work by detecting electromagnetic radiation from an object with wavelengths longer than those of visible light (from about 800 nanometer [nm] to 1 millimeter [mm]), which are not generally visible to the naked eye (Figure 4 and Figure 5). A glossary of terms used to describe IR/thermal systems in this paper is provided in Appendix A Glossary of terminology for evaluation of infrared/thermal technology as applied in this paper. Wavelengths in these IR ranges are emitted by heated objects (Bryant 2007). IR night-vision equipment functions by detecting differences in temperature between an object and its surroundings. Warm-blooded animal detections rely primarily on differences in IR emissions between an animal's body temperature or its exhalation and the temperature of the surrounding water or air. At distances greater than approximately 500 m, IR detection is based upon exhalation only.

IR/thermal imaging uses a charge-coupled device (CCD) to detect photons (physics term defining a fundamental particle of light) emitted in the IR portion of the visible spectrum. Real-time processing software analyzes differential wavelengths to effectively determine heat levels at the source of photon transmission (water, animal skin, exhalation/blow). Differences in temperatures are then represented on a display as different colors - typically shades of gray. Additional software processing is sometimes used to artificially color areas of significant temperature differential, e.g., red for a relatively "hot" region and blue for a relatively "cold" region. FLIR notes that various IR color palettes can be applied to different personal preferences, environments, and situations. Grayscale imaging is preferred over synthetic color enhancements for its consistency for observation and when trying to develop automated detection solutions.

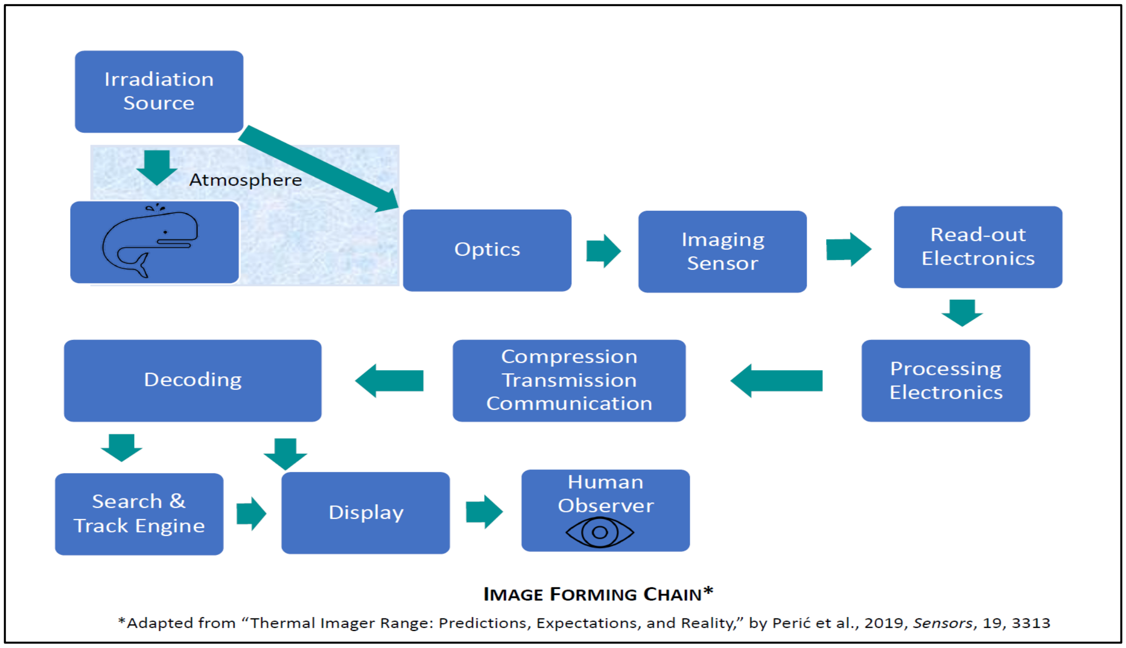


**Figure 4. Flow diagram illustrating thermal imaging process starting with detection of an irradiation source associated with a whale blow through the processing steps until the information reaches the human observer eye.**

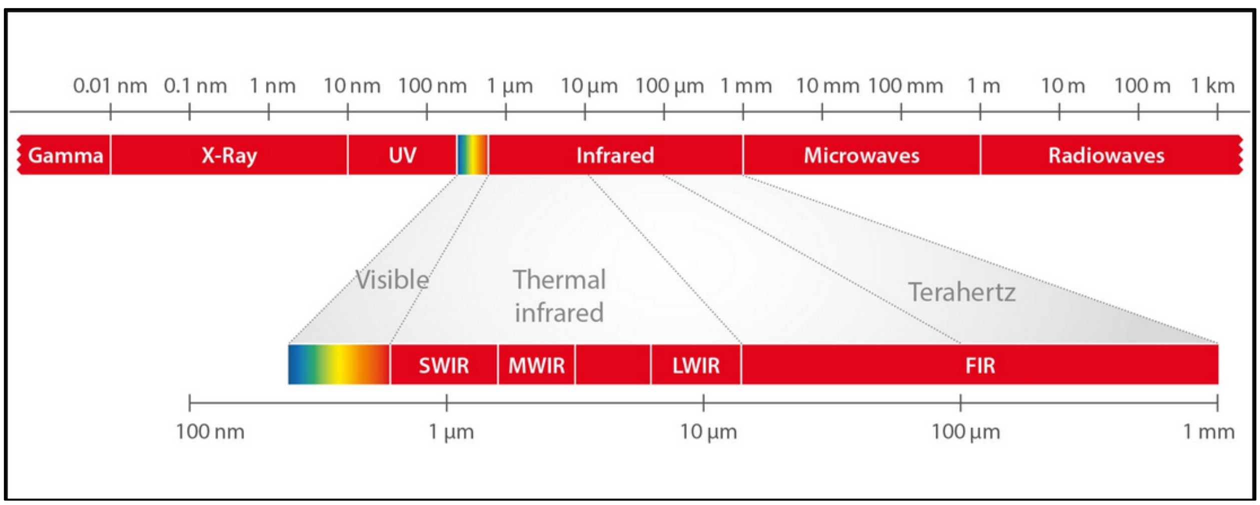


**Figure 5. Infrared wave length spectrum (Source: Perić et al. 2019).**

### 3.1.1 Key Factors Affecting IR/Thermal Device Performance

Performance, suitability, and selection of a particular IR solution to detect cetaceans at sea depend on a number of key extrinsic and intrinsic factors related to the goals for the solution (e.g., species of interest, distance and degrees of view area being monitored, environmental conditions). IR solutions are affected by the following properties for any design consideration.

- Type of sensor – Cooled or uncooled. Cooled sensors can support either long wave (LW) or medium wave (MW) parts of the IR spectrum. Uncooled sensors only support the LW part of the IR spectrum. Cooled sensors have higher sensitivity for detecting temperature differentials which enhances the ability to distinguish animals from the surrounding medium (Zitterbart et al. 2013; Horton et al. 2017).
- Sensor resolution – The number of pixels provided by the sensor. The higher the number the better the resolution, thus the higher likelihood of target recognition. Newer systems are arriving on the market available at 1280x1024 versus older, lower-resolution systems at 640x480. Approximately 8 pixels on a sighting are required for target recognition of whales. The Johnson Criteria suggests 2 pixels are needed for 'detection' and 8 pixels are needed for 'recognition' (see Appendix B Definitions of the three levels of detection performance applied by the Johnson Criteria for modeling the theoretical performance of an infrared thermal imager (Sjaardema et al. 2015).[1]).
- Sensor bit depth (per pixel) – Bit depth addresses the amount of information per pixel that can be stored. The higher the bit depth, the richer the image quality. Industry trend is moving from today's 8-bits depth to 14 in support of image quality, thus recognition, and artificial intelligence (AI) development for augmented detections.
- Optics FOV – Addresses the breadth and height of what an optics system can see instantaneously. It can be addressed more commonly in degrees, width by height. FOV can be fixed or variable via optical zoom.
- Lens quality and zoom – Lens quality speaks to intrinsic losses that imagery suffers passing through a given optical lens. This is typically not a concern when using a high-grade mountable IR camera. Optical zoom means the FOV can be narrowed via mechanical or digital manipulation of a lens focal plane, resulting in a higher-resolution image of a sighting. Digital zoom provides zoom by image clipping, thereby reducing image quality and as such is not recommended for use in detecting marine mammals at sea.
- Camera mount placement and height – Height ASL or azimuth angle allows for increasing sighting distance and probability of detection. Height enhances a particular camera's ability to distinguish between targets and the surrounding medium (Horton et al. 2017) most notably at distance. Consideration for mounting any camera should include eliminating super structure interference or sensor saturation due to heat sources such as that from exhaust stacks.
- Platform stability – Image stability is especially important in the removal of blur induced by ship vibrations and ocean swells/waves. Mechanical stabilization is a preferred solution. Stability can be improved by mounting the camera on a high range of motion stability platform that seeks to keep the camera aligned with the horizon (Zitterbart et al. 2020a). Digital stabilization has been reported, anecdotally, to provide minimal value for use in detecting marine mammals at

sea due to image clipping techniques employed to give the appearance of a stable image.

- Pan rate – Panning (i.e., scanning) an area is a means to increase the ability of a given camera to adequately cover a greater area of ocean. Coverage is increased by rotating the camera head by a predefined fixed rate. However, panning has the potential to result in missed detections. Detection probability is determined by the pan rate relative to the time window or availability of the target for detection (i.e., the viewable lifespan of an individual whale blow, averaging approximately 4-5 sec as illustrated in Figure 6). In the case of an IR camera system mounted on a vessel, panning involves mechanically swiveling the camera head at the necessary rotational speed to provide sufficient coverage across the camera's assigned search radius to capture the target (e.g., a whale blow) during the brief period a given target is available to be detected. Identifying a camara's optimal panning configuration is complicated by two potential issues: (1) Panning too fast can cause motion blur which diminishes image quality to the point of reducing the probability of detecting a desired target when it is available to be detected; (2) panning too slowly can result in the camera missing a detectable target altogether.
- 360° concurrent coverage – Complete concurrent, simultaneous coverage of a 360° view is possible with a single or multiple mounted IR cameras (discussed further in Sections 5 and 6). The single camera system design provides a full 360° view by either spinning a sensor with a frequency of multiple revolutions (approximately 5 hertz [Hz]) per second, or by using a fixed platform ring of sensors properly spaced to provide a 360° composite view. The spinning sensor model has been used successfully for marine mammal detection from vessels (e.g., Smith et al. 2020; Zitterbart et al. 2020a). This type of platform represents the highest-quality device with very low occurrence of missed detections within its detection range. The camera is highly effective when paired with image-recognition software for remote playback to PSO review and acceptance, resulting in very low false negatives (discussed further in Section 6).

In addition to the above factors, extrinsic meteorological and oceanographic conditions can confound attempts to detect marine mammals (Figure 1 and 7). Examples include high winds, swells and Bft, low- and no-light, and poor visibility due to fog, glare, precipitation, or cloud cover. Camera performance varies based upon atmospheric attenuation factors and in low-angle sunlight (sunset, sunrise). IR effectiveness is diminished under high glare conditions. LW sensors outperform MW sensors in these conditions. The International Civil Aviation Organization (ICAO) has outlined IR effectiveness in a range of fog conditions (Table 2).

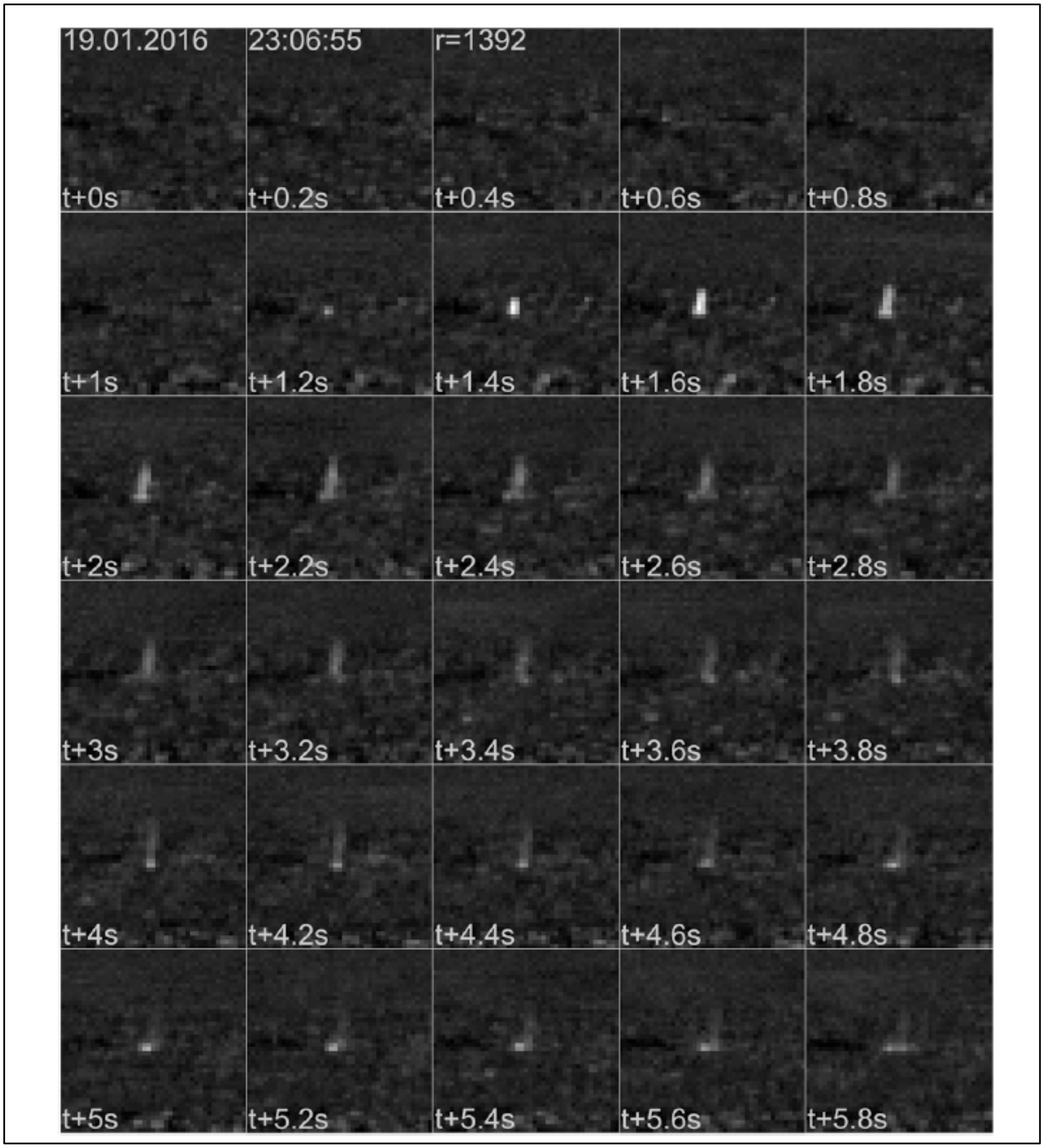


**Figure 6. Video clips from a thermal infrared (IR) camera of a humpback whale blow taken at a distance of 1,392 m illustrating the duration of time the blow was visible/detectable as a white feature on the IR camera monitoring screen (Source: Zitterbart et al. 2020a).**

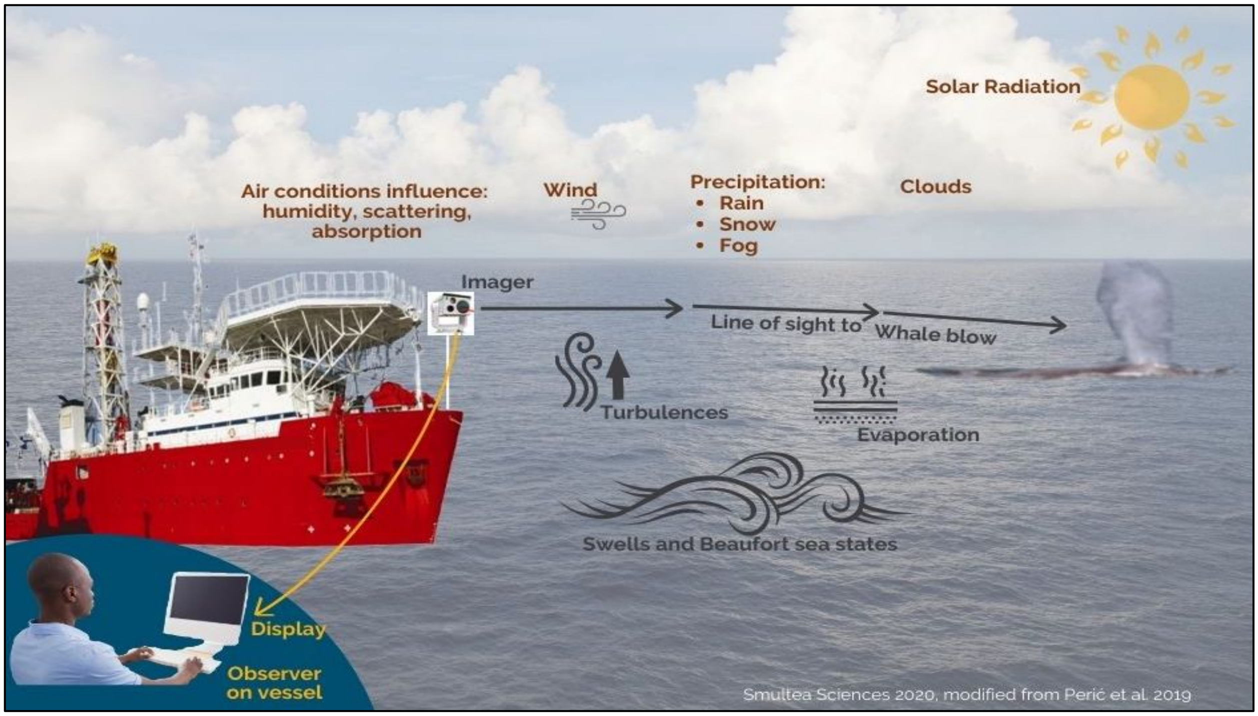


**Figure 7. Extrinsic factors influencing the ability to detect marine mammals using thermal infrared imaging systems (Source: modified from Perić et al. 2019).**

**Table 2. Visual ranges and thermal perceptibility based on International Civil Aviation Organization (ICAO) fog categories for medium wave (MW) infrared (IR) versus long wave (LW) IR camera systems**. The LW IR camera system outperforms the MW IR camera system in Cat I and II fog categories (see FLIR n.d.).

| THERMAL PERCEPTIBILITY | | | |
|---|---|---|---|
| ICAO Fog Category | Visual range [km] | MW IR range [km] | LW IR range [km] |
| Cat I | 1.22 | 3.0 - 9.8 | 5.9 - 10.1 |
| Cat II | 0.61 | 0.54 | 2.4 |
| Cat III a | 0.305 | 0.294 | 0.293 |
| Cat III c | 0.092 | 0.089 | 0.087 |

Perceptibility range in 3 optical bands, assuming a 10℃ SNR and a 0.15℃ detection limit.

### 3.1.2 Theoretical Modeling of IR/Thermal Device Performance

Mathematical models are available to predict how a range of both extrinsic and intrinsic conditions can affect NVD/IR detection effectiveness (e.g., ModTran, U.S. Army NV-IPM, Johnson Criteria; Figure 8). These models are applied and accepted as standard operating procedure by military, aviation, and other entities to evaluate theoretical conditions for thermal device performance. Model input choices can range from perfect to variable environmental conditions (e.g., different levels of humidity, ambient temperatures, etc.). However, standard manufacturer estimates of detection range typically reflect idealized (perfect) environmental conditions and do not necessarily reflect real-world conditions. A common theoretical model applied to estimate effective distance performance of a thermal imager is the Johnson Criteria (Sjaardema et al. 2015). The model estimates the maximum range that an object can be discriminated with 50% probability by an optical system based on three ascending levels of resolution: (1) detection, (2) recognition, and (3) identification (Appendix B Definitions of the three levels of detection performance applied by the Johnson Criteria for modeling the theoretical performance of an infrared thermal imager (Sjaardema et al. 2015).[1] and Figure 8). This simplistic model only considers geometrical factors and does not account for extrinsic factors (e.g., environmental conditions, elevation, etc.). However, the Johnson Criteria has continued to be successfully applied over the last 30 years and continues to be useful for simplified range predictions for thermal imaging devices (Perić et al. 2019).

Final interpretation of manufacturer reported device performance and application to real-world conditions should be interpreted with caution, depending on the sophistication of mathematical modeling approach as applied to the target application (marine use).

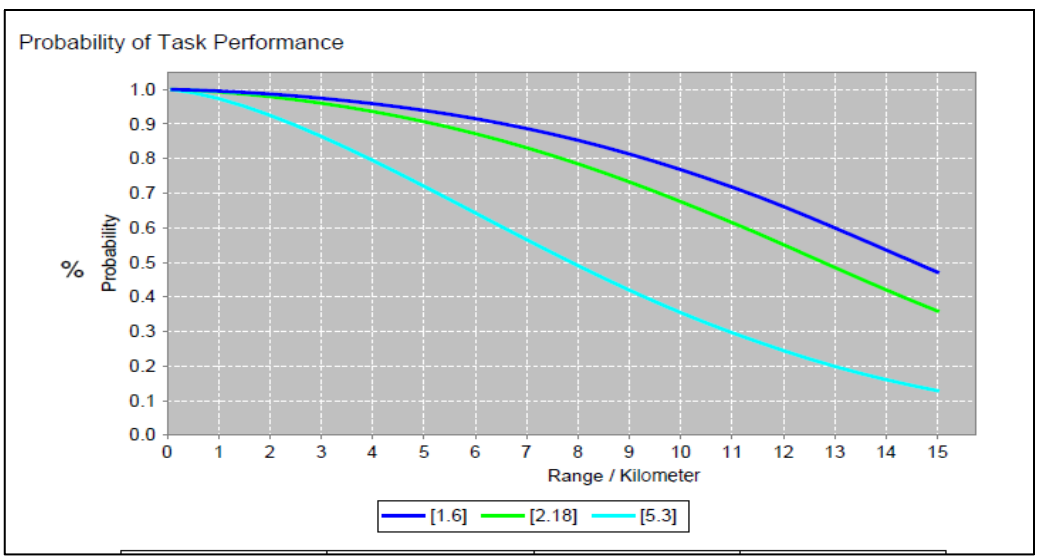

**Figure 8. Probability of detection of a human on land by distance using U.S. military modeling based on three levels of detection (from lowest to highest resolution): blue = detection, green = recognition, turquoise = identification (see Appendix A Glossary of terminology for evaluation of infrared/thermal technology as applied in this paper for definitions). (Source: NVTS 2020).**

### 3.1.3 Advantages and Disadvantages of IR/Thermal Technology

Below we summarize the advantages and disadvantages for using IR/thermal technology for detecting marine mammals at sea, including as reported by Zitterbart et al. (2013, 2020a,b), Horton et al. (2017), Verfuss et al. (2018), and Smith et al. (2020).

*Advantages*:

- Available specific, cooled one-camera IR systems have been empirically demonstrated to provide concurrent 360° coverage and high probability detection of whale blows (>90%) ~1.5-2+ km from vessel platform heights of 15-20+ m ASL (e.g., Smith et al. 2020; Zitterbart et al. 2013, 2020a,b).
- Multiple mounted cooled or uncooled IR cameras can be combined to provide full 360°concurrent coverage with theoretically modeled high detection probability under same conditions as above.
- Automated event (sighting) recognition/detection software, when combined with specific cooled sensor features, has been shown to facilitate detection at sea in near real time out to ~5+ km, out-performing PSOs in some situations (Smith et al. 2020; Zitterbart et al. 2013, 2020a,b), and reducing the probability of undesirable false negatives (see glossary in Appendix B Definitions of the three levels of detection performance applied by the Johnson Criteria for modeling the theoretical performance of an infrared thermal imager (Sjaardema et al. 2015).[1]).
- Availability of newer generation higher sensor resolution, pixel bit depth, optics quality, and platform stabilization, and height ASL maximizes detection effectiveness (i.e., detection range).
- Cooled and uncooled LW systems perform better than cooled MW systems in no to low-light/low-visibility conditions (e.g., darkness), including some humid conditions (e.g., light rain, snow, glare, haze, fog; see Table 12).
- Remote monitoring of the IR device's view via video feed and remote monitor is less fatiguing for PSOs than visual monitoring using handheld NVD or IR devices over extended periods (Smultea et al. 2019; Smultea Sciences 2020), especially when coupled with automatic detection algorithms.
- IR video/images can be recorded for near real-time immediate and later review (helps confirm detection/taxa). Image capture method that allows quick replay and timely review of suspected events of interest allows for quick confirmation and mitigation decisions, and improves the quality of sightings.
- Detection of small cetaceans and pinnipeds at sea within several kilometers is possible with some recent cooled and uncooled IR sensor technology and devices, particularly cooled LW systems.
- Effective for cold- to warm-water conditions (-1.8 to 22.7° Celsius [C]).

*Disadvantages*:

- 360° view may require multiple cameras which may have installation limitations due to vessel layouts (e.g., partial view obstruction). Camera acquisitions typically require 3-6+ month delivery time.
- 360° all-in-one systems are available but at higher cost and longer delivery time (6-12+ months), are more expensive, and require maintenance burdens.
- Optical view of each camera is limited to its immediate FOV.
- Ability to detect smaller cetaceans using uncooled sensors (especially single animals/small groups) tend to be limited to distances of <500 m.
- Detection probability quickly drops with deteriorating extrinsic humidity factors (e.g., fog, rain, snow). No single visual detection solution has been identified to fully eliminate this constraint (though some solutions perform better than others in some humid conditions; Table 2).
- Performance in sunlight and low-angle sunlight (sunset, sunrise) diminishes due to glare effects. LW sensors have been demonstrated to outperform MW sensors in these conditions.
- To our knowledge, there is only one IR image detection software (AIMMMS 360° platform) empirically tested to reliably and consistently detect whale blows with high detection probability (e.g., Zitterbart et al. 2020a).
- Operation of high-end cooled IR camera system has required a dedicated, on-site trained engineer (e.g., Smith et al. 2020).

## *3.2 Low-light Amplifying Devices*

Low-lighting imaging (or low-light enhancing/amplifying) night-vision equipment functions by amplifying ambient light from the moon, stars, and artificial light sources to brighten the visual field, thereby improving the chances of detecting an object reflecting the available light.

The most common method of low-light imaging (also known as image intensification, amplification, or enhancement) uses a device called an image intensifier to amplify available visible light. Available light is focused through the objective lens (the lens closest to the object being viewed) onto the photocathode (a photosensitive surface that emits electrons in response to light or other radiant energy) of the image intensifier. Amplified light is then used to display the image on a monitor such as a binocular/monocular, video, or a photograph to the observer.

Low-light imaging technology has undergone multiple improvements over the last few decades as expressed by the level of device “generation.” Note, however, that the performance of these devices is traditionally based on performance in terrestrial environments (e.g., for military use or hunting) rather than for marine applications and at-sea conditions. Updated products are referred to as relative to a particular generation (e.g., Gen 1, Gen 2, Gen 3). Newer generation products (i.e., Gen 3) have higher signal-to-noise ratios than previous versions, allowing more effective management of conditions with high light pollution associated with urban areas. This includes, for example, providing reduced “halo” effects around images. Typically, the newer generation devices are marketed for use in urban areas. It is assumed that higher-generation devices bring value to low-light environments seen at sea as well, although this assumption remains to be systematically validated and tested.

Low-light enhancing devices are reported to be routinely capable of detecting targets to distances of up to 200 m or more, including cetaceans at sea, depending on observation/environmental conditions. Further, such devices are available at relatively low costs compared to other night-vision devices capable of detecting cetaceans at sea (e.g., IR). However, systematic studies and reports on the effectiveness of light-amplifying devices for detecting cetaceans are generally lacking in the literature.

A paucity of literature and systematic studies on low-light enhancing device effectiveness is likely due to their relatively poor performance when very little or no ambient light is available, such as new moon phases (or set moon) and cloudy skies. Thus, based on available data, it appears that effective performance of such devices to within a 200-m distance is limited to specific conditions (e.g., sufficient ambient light, no fog or precipitation, Bft less than around 4). Such devices are considered ineffective in very low-light or no light conditions (e.g., cloudy or moonless nights), too much incident light (e.g., direct vessel lights), fog, precipitation, and high sea states.

Specific extrinsic factors that negatively affect the effectiveness of low-light enhancing devices include: low observation height above water, lack of moonlight (or urban reflection) at night, clouds, fog, glare, rain, sea state (typically at Bft 3), and snow.

# 4 Literature Overview

## 4.1 Studies Selected for Review

We queried several literature databases of over 20,000 scientific/technical papers and conference presentations at our disposal. From this general search and these sources, over 50 papers and reports were accessed. Our full review of the available literature is summarized in Appendix C Summary of most relevant, selected literature reviewing effectiveness of night vision technologies for detecting cetaceans, pinnipeds and sea turtles and described in detail in Appendix E Literature review, with references provided in Section 7.3 *Literature Cited*. Below is a summary of our findings.

## 4.2 Summary and Conclusions of Literature Review

### 4.2.1 Historical Perspective

Work on NVD use for detecting marine mammals began in the 1980s accompanying a growing general interest in field studies of marine mammals. This interest was coupled with an expansion of offshore resource utilization requiring mitigation and monitoring to minimize potential adverse impacts to marine mammals. This was driven, at least in part, by emerging interests in improving knowledge about basic marine mammal biology, occurrence, and behavior, including their diurnal behavioral patterns.

Endangered/threatened status for some species also prompted conservation actions as related to human activities, including offshore energy development. Most studies we reviewed were conducted from vessels, with some feasibility studies conducted from land. Vessel-based work arose from the need to monitor the presence/absence of protected species in the immediate vicinity of certain operations. In contrast, shore-based work tended to focus on determining if devices might successfully detect marine mammals at significant distances. Devices studied included cooled and uncooled thermal imaging, binoculars, monocular, spotting scopes, and various types of camera systems, among others.

Most authors concluded that light-enhancing devices and NVD *could* be used to detect marine mammals. However, few studies provided long-term, systematic, and repeatable observations of the relative effectiveness of these devices. Shortcomings and caveats accompanied the studies such as a limited number of observations and negative influences of environmental conditions that were not systematically evaluated/assessed.

### 4.2.2 Recent Advances

Advances in NVD technology and experimental work to determine their feasibility for marine mammal detection have accelerated in the last 10 or so years (Appendix C Summary of most relevant, selected literature reviewing effectiveness of night vision technologies for detecting cetaceans, pinnipeds and sea turtles). These studies have empirically and systematically demonstrated that high-end military thermal devices are reliably capable of detecting whales at distances of at least several kilometers from large vessels and shore, including utilizing image recognition software (e.g., Zitterbart et al. 2013, 2020a,b; Smith et al. 2020). Small cetaceans (e.g., Dall's porpoise) and pinnipeds also have been detected reliably at distances of ≥1 km using the same system (e.g., Weissenberger et al. 2011; Weissenberger and Zitterbart 2012).

### 4.2.3 Effectiveness by Distance

As noted earlier, reaching overall conclusions regarding detection distances is a challenge because studies reviewed had unique objectives, involved a number of platforms, and evaluated various devices. Thus, inter-study comparisons regarding detection distance can be difficult. Nonetheless, we note that nearly all studies reported some cetacean detections within 200 m (Appendix C Summary of most relevant, selected literature reviewing effectiveness of night vision technologies for detecting cetaceans, pinnipeds and sea turtles and Appendix E Literature review). For example, at least one study (e.g., Yonehara et al. 2012) confirmed all sightings within 150 m, but noted that the incidence of detections began to decrease at distances over 500 m, and in some cases confirmed detection ranges were below 500 m (e.g., Graber 2011; Horton et al. 2017). In contrast, some authors (e.g., Weissenberger and Zitterbart 2012; Ellis et al. 2012) reported detection distances up to or exceeding 1,000 m. Maximum reported distances were "up to 8,000 m" (notably, Perryman et al. 1999; Sullivan 2016; Sullivan et al. 2015); however, these involved land-based studies whereby elevations allowed substantially distant survey areas and a very stable observation platform. In general, they noted the ability to detect whale blows at these distances, but did not report whether these were repeated, consistent detections. Work by Zitterbart and colleagues (e.g., Zitterbart et al. 2011, 2013, 2020a,b) have provided perhaps the most rigorous and repeated trials of IR devices, involving multiple cruises in various oceans, and reported consistently being able to detect whale blows up to 5,000+ m.

### 4.2.4 Pinnipeds and Sea Turtles

We found little information on detecting pinnipeds and sea turtles in the water using light-enhancing or IR devices. Most available work has focused on hauled out pinnipeds and nesting sea turtles on land. Available in-water study results tend to be opportunistic as summarized in Appendix C Summary of most relevant, selected literature reviewing effectiveness of night vision technologies for detecting cetaceans, pinnipeds and sea turtles. Reviewed studies indicate that pinnipeds and sea turtles have been detected using light-enhancing and mounted uncooled IR devices within about 100-200 m and rarely beyond this distance, especially sea turtles (e.g., Smultea et al. 2019). An exception is the Rheinmetall cooled IR camera system which detected most walruses surfacing within 1 km of a seismic vessel in the Arctic, with some individuals detected to as far as 1.5 km; detection and tracking software also detected the path of swimming walrus while the seismic observation vessel passed the animals (Weissenberger et al. 2011; Weissenberger and Zitterbart 2012).

### 4.2.5 Results in the Context of U.S. Atlantic Offshore Wind Construction Mitigation and Monitoring Objectives

The primary objective of this literature review was to assess night vision technology relative to utility and efficacy for detecting marine mammals in the U.S. North Atlantic, focused on endangered whales during offshore wind construction, maintenance, and operations. In particular, our objective was to assess the ability of such devices to consistently and reliably detect these species within several kilometers around a stationary platform producing noise (e.g., pile driving) requiring mitigation and monitoring by PSOs from a typical elevated offshore observation vessel. However, empirical data for directly assessing these devices in this setting are few based on available literature. Exceptions include recent unpublished small-vessel based testing of a pilot IR system off Massachusetts (Zitterbart et al. 2020b), vessel-based systematic studies off eastern Canada using the Rheinmetall and AIMMMS IR system (Smith et al. 2020), a summary analysis of a subset of 2018-19 Ørsted PSO data using handheld IR and NVD and mounted uncooled cameras (Smultea et al. 2019), and single survey, Lease Area or IHA permit-related technical reports to NMFS and BOEM (e.g., Smultea Sciences 2017, 2018, 2019, 2020).

Available information combined with findings from studies in other geographic locations indicate the existence of proven and reliable, high-end mounted cooled thermal systems capable of detecting whale blows within approximately 1.5-3 km with high detection probability (>90%) in a concurrent 360° arc. Theoretical modeling and opportunistic detections with other cooled and uncooled IR systems provide strong evidence that the associated optical features are capable of reliable detection of whale blows out to 1-2+ km from observation heights of about 15-20+ m ASL, depending on environmental conditions. The current limiting factors for the latter systems with respect to offshore wind construction activities is that multiple cameras are needed to provide effective concurrent 360° coverage, given FOV limitations as discussed below in Sections 5 and 6.

### 4.2.6 Further Study Needed

There remains a clear need for systematic studies with sufficient data collection to empirically test theoretical model performance and draw comparisons between devices. Such studies should involve repeated trials under various conditions to objectively and systematically assess the capabilities of each device to reliably and consistently detect marine mammals during darkness/low-light conditions at various distances. Further detail on devices and features available and/or used to detect marine mammals are reviewed below.

# 5 Reviewed Devices and Features

## *5.1 Evaluation Approach*

To establish a process for evaluating suitable NVD features, we first cast a broad search to identify specific IR and light-enhancing devices that have been used in studies and/or are currently being used in the field to detect marine mammals, including for mitigation and monitoring (Table 3, Table 4, Appendix D Summary of researched devices (listed alphabetically).). Our search relied primarily on published literature, readily available unpublished literature, communications with professionals working in this field, and our own knowledge and experience working with this technology. We also drew upon conversations with others knowledgeable on the subject or having done previous research on this or related topic(s): K. Baker, BOEM; D. Zitterbart, Woods Hole Oceanographic Institution; S. Kraus, New England Aquarium. This included contacting various IR device manufacturers and engineers, some of whom provided results of theoretical modeling for certain devices and scenarios (e.g., Current Scientific Corporation, FLIR, NVTS, Seiche Ltd.). Manufacturer web sites, marketing materials, and related information were also consulted.

We then compiled a table (Table 5) of IR/thermal device features and specifications that we considered met the purpose of this paper: to identify an IR/thermal system capable of detecting whale blows within a 360° view around a stationary vessel platform out to approximately 2 km with relatively high detection probability during offshore wind construction, operations, and maintenance activities.

From our initial list of devices, we next compiled a table of up to four example device models we evaluated as capable of probable detection of cetaceans within each of four distance categories commonly or anticipated to be applied in mitigation and monitoring of marine mammals: 0-200 m, 201-500 m, 501-2000 m, and >2000 m (Table 6).

Our initial research involved reviewing 18 devices (Table 4) based on

- their relevance to the objectives of this review;
- sufficient information (e.g., make/model, manufacturer, data on performance) having been provided in a given study to support a detailed examination;
- relative cost to provide a basis for evaluation of cost-effectiveness relative to technological tradeoffs; and
- utility for PSO detection of cetaceans and other marine mammals from large vessels associated with offshore wind construction, operations and maintenance, focusing on distances of around 2 km and beyond.

Devices were considered acceptable from a perspective of:

- Operating temperature
- Power requirements
- Reported performance history
- Photo/video capabilities

Some performance parameters were estimated via inference from the reviewed literature. As a result, indicated performance may be inconsistent with manufacturer data that are often based on trials using large, “hot” objects on land rather than whales or other marine mammals, and as tested in near perfect atmospheric or ambient conditions. Manufacturer-published detection distances were often unrealistic because they did not factor in use for studies of marine mammals.

## *5.2 Overview of Findings*

Twelve manufacturers are represented by the example devices listed in Table 3 and Appendix D Summary of researched devices (listed alphabetically). Maximum effective detection distances by device ranged from about 100 m to 5,000+ m (although some distances were determined on land and involved inanimate objects such as buildings). With respect to distance, handheld light-enhancing devices are considered adequate to reliably detect cetaceans at sea to approximately 150-200 m; for pinnipeds and sea turtles, this maximum is about 50-100 m (e.g., Smultea et al. 2019; see Appendix C Summary of most relevant, selected literature reviewing effectiveness of night vision technologies for detecting cetaceans, pinnipeds and sea turtles and Appendix D Summary of researched devices (listed alphabetically).). Beyond 200-500 m, a mounted IR thermal system is recommended to improve detection capabilities.

Cooled sensors with LW imaging sensors are reported to perform better at farther distances than uncooled systems due to higher sensitivity to temperature differentials. Both cooled and uncooled LW and MW IR cameras appear to perform adequately to within approximately 1.5-2 km when used at sufficient height ASL (>15-20 m), under stable conditions, and in tenable environmental conditions (Beaufort <4-5, no obscuring rain, fog, snow). In general, note that detection of individual small marine mammals or small such groups (i.e., less than approximately 3-5 individuals) is difficult at distances over approximately 100-200 m using all devices reviewed herein; this is due to limited FOV, resolution, and/or capacity to detect temperature differentials from relatively small, fast-moving animals.

Estimated costs (Table 6) ranged from approximately \$3,500 to \$750,000+ to purchase, and about \$175 to \$10,000+/day to rent. A range of pros/cons were considered, including weight and relative ease of handling, the extent of FOV (e.g., 360° scanning capability), resolution, and whether alerts are routinely provided when the instrument acquires a detection. In general, cooled systems are considerably more expensive to purchase and maintain than uncooled systems, given their higher-quality resolution, signal-to-noise ratio, cooling system, and improved capabilities in humid conditions, among others. There is a direct corollary between system ‘completeness’ and system expense. The more complete and high-end the bundled solution, the higher the costs for either purchase or lease options. This is readily reflected in the pricing tables (Table 6).

An additional consideration for selection and installation of a mounted IR camera system is equipment weight. Weight and bulk affect installation design considerations. Heavy weight can impact crew and equipment requirements and logistics for onboard system placement and securing. Weight is presented here only as a precaution to any final solution that may be selected.

We also provide links to device manufacturers and additional device specifications where known (Table 7 in Section 7 "References").

### 5.2.1 Infrared/Thermal

Earlier in this paper we gave a comprehensive overview of IR/thermal imaging technology, key factors affecting device performance, theoretical modeling of device performance, and advantages and disadvantages of IR/thermal technology.

Of note, recent research points to the high value of image detection software for providing playback review to PSOs for marine mammal detection confirmation (Smultea et al. 2018, 2019, 2020). A typical PSO can process up to approximately 6 detections per minute using the latter technology.

The only known 360° detection solution within one camera system (of which we are aware) with an empirically proven high reliability of detection is the Rheinmetall AIMMMS solution. A second 360° solution is now in development by one manufacturer. While multiple mounted IR cameras can be used to concurrently cover a 360° view, their reliability in terms of probability of detection at sea for cetaceans has not been systematically tested to our knowledge; however, theoretical modeling and available camera optics indicate that this is possible to within approximately 2 km from a stable platform of sufficient mounting elevation (see Table 5 and Table 6).

Significant review papers, including a relatively recent study, present results of a triple blind study comparing PAM, PSOs, and IR detection methods and further review of suitability of sensor types (low-light, IR) (e.g., Smith et al. 2020, Zitterbart et al. 2020a). Zitterbart et al. (2020a) also collected sufficient data to determine that in some cases and circumstances, IR cameras coupled with auto-image recognition software outperformed experienced marine mammal observers by making more detections.

At the time of this writing, the low-resolution 'thermapen' type handheld IR detector (a model reviewed here) is not recommended for use in detecting marine mammals from vessels. PSOs field tested a thermapen from a vessel off Massachusetts and reported it to be of insufficient relative resolution to detect objects beyond ~50 m; in addition, its relatively wide field of view appeared to sacrifice resolution at distance (Smultea Sciences, unpub. data, 2017).

### 5.2.2 Low-light Amplifying Imaging

Also discussed earlier is an overview of low-light amplifying devices. To summarize, use of low-light amplifying imaging solutions has been shown to be good for sunrise/sunset periods and when there is good illumination from the moon. In all other cases these systems provide limited value outside of about a 200-m radius assuming sufficient FOV, especially in comparison to the quality of mounted IR-based devices. In no-light conditions (i.e., no moon, cloudy sky) these devices are rendered essentially ineffective. It is recommended that use of low-light imaging be limited to use at distances <200 m or as an accompaniment to more capable mounted IR systems when the maximum mitigation/detection zone is >200 m. In some conditions, handheld low-light amplifying devices perform better than handheld IR devices at distances <200 m (Smultea et al. 2019).

**Table 3. Technical specifications of infrared (IR) systems selected for review (presented in alphabetical order).[1]**

| Model[1] | Field of View (Degrees; or Horiz x Vert) | Detector Type[2] | IR Focal Length | Resolution | Pan/Tilt |
|---|---|---|---|---|---|
| AGM-HS Gen 3 Hand Select Night Vision Monocular | 40° | Uncooled LW planar | 26 mm | 64-72 lp/mm[3] | N/A |
| Current Scientific Corporation Night Navigator 2526 | 8.3 - 52.5° Choice of multiple lenses available | Uncooled LW planar | 25 - 75 mm 3X optical zoom | 640 x 480 1280x1024 expected in year 2021 | Variable 360° pan at 40° per second, tilt -90° / +30° |
| Current Scientific Corporation NN6056 | 1.7 - 32.2° | Cooled MW | 22 X optical zoom | 640x512 | |
| Current Scientific Corporation NN8000 | 180/360° FOV | Uncool LW coupled with Cooled MW | Uncooled – fixed 52.5° Cooled Varying | Uncooled 1280x1024 cooled up to 1280x1024 | Uncooled 360° continuous Cooled 360° with a seek rate of 90° per second |
| FLIR M400 Thermal Machine Camera | 6 - 18° | Uncooled LW planar | 35 - 105 mm 4X optical & 4X digital zoom | 640 x 480 | variable 360°, +/- 90° tilt |
| FLIR Ocean Scout 640 | 18 x 14 | Uncooled LW planar | 4X digital zoom | 640 x 512 | N/A |
| FLIR MD625 Thermal Imager | 25 x 20 | Uncooled LW planar | 25 mm 4X zoom | 640 x 480 | N/A |
| FLIR M324XP | 24 x 18 | Uncooled LW planar | 19 mm 2X zoom | 320 x 240 | 360° pan +/- 90° tilt |
| FLIR Armasight Command Pro 336 | 13 x 10 | Uncooled LW planar | 25 mm 4X zoom | 640 x 480 | N/A |
| FLIR ThermaCam Ex series | 45 x 34 | Uncooled LW planar | unknown, no zoom | 120 x 90 | N/A |
| NVTS Reliant 640HD | 15.5 x 11.6 | Uncooled LW planar | 40 mm 4X digital zoom | 640 x 480 | 360° pan -15x90 reversible |
| NVTS Guardian 4HD | 25.5 x 21 | Uncooled LW Planar | 15 – 300 mm 20X optical zoom | 640 x 512 | 360° pan -60 x 70 reversible |

| Model[1] | Field of View (Degrees; or Horiz x Vert) | Detector Type[2] | IR Focal Length | Resolution | Pan/Tilt |
|---|---|---|---|---|---|
| Rheinmetall AIMMMS | 360 x 18 | Cooled LW rotating line scanner | unknown | 640 x 480 | rotating line scanner giving 360° FOV and 12° tilt |
| Seiche HD Thermal Camera | 18° | Uncooled LW planar | 4X digital zoom | 640 x 480 | 120° pan |
| Seiche Dual Camera System (supersedes HD Thermal above) | Six options - 7.5 mm to 50 mm fixed | Uncooled LW planar | 8 X digital zoom | 640x480 | +/- 168° pan<br>-90 x 25 |
| Xenics | 4.2 - 42° range of lenses | Cooled MW planar | Up to 210 mm | 640 x 480 | fixed |

[1] Listed is published information. Omissions are due to either manufacturer or research data not readily available.
[2] Most uncooled planar-based detectors are Vanadium Oxide (VoX) long–wavelength (*i.e.*, 7.5–14μm) microbolometer, thermal sensitivity of <0.05°C unless noted otherwise.
[3] lp/mm: a metric for resolution indicated as 'line pairs per millimeter'.

**Table 4. Technical specifications of night vision device (NVD; i.e., low-light amplifying/enhancing) imaging systems known to be in use for detecting cetaceans at sea.**

| Model | FOV (Degrees) | Detector type | Focal length | Resolution | Pan/Tilt |
|---|---|---|---|---|---|
| ATN PVS7-3 night vision goggles | 60° | Unknown | 27 mm | 64 lp/mm | N/A |
| Electrophysics Astroscope[1] | Depends on lens type used | Unknown | Depends on lens type used | Depends on lens type used | N/A |

[1]Manufacturer data currently unavailable at the time of this writing. This device is mentioned here to acknowledge its recent use for sea-based mitigation work (e.g., Lee and Nenadovic, 2017).

**Table 5. Recommended minimum infrared thermal camera specifications and conditions to achieve high level (>90%) probability detection of large whale blows for mitigation and monitoring within 2 km from an offshore observation platform.**

| Parameter/ Condition | Recommended Target Metric | Comments | Limitations | Source |
|---|---|---|---|---|
| Cooled vs. uncooled IR camera system | Cooled outperforms uncooled but some uncooled considered adequate to ≤2 km | Cooled system outperforms uncooled system, particularly at farther distances (e.g., higher resolution). LW IR preferred over MW IR (higher resolution, better performance in humid conditions). LW IR has higher resolution & performs better in adverse atmospheric conditions than MW IR | Lead time to build Rheinmetall is 6-12 months and 6 months for Current Scientific Corporation & NVTS models. Importation to U.S. from overseas may require special export/import permits | |
| Field of view | > 25-55° | Wider FOV facilitates greater areal coverage at expense of image size at distance | Narrower FOV requires more cameras to provide full concurrent 360° view | |
| Thermal image sensor type/wavelength/ pixel pitch | 1280 x1024 HD (LW IR)/ 8-14 microns/ 10 µm HD, 15 µm VGA | Emphasis is given to LW uncooled solutions due to their reported capabilities out to 2 km, lower cost of acquisition, and significantly lowered maintenance burdens | Atmospheric conditions | |
| Lens | 15-300 mm zoom, F4, 20x optical zoom. Autofocus | Mechanical zoom has higher resolution than digital zoom; zoom is used generally for greater image recognition at the cost of FOV | Digital zoom gets pixelated quickly resulting in reduced image resolution, thus mechanical zoom better for detection resolution | |
| Stabilization mechanism | Mechanical stabilization (e.g., gyro stabilization) | Digital stabilization results in reduction of useful image size due to image clipping undertaken to eliminate appearance of vibration, and as such should be avoided. | | |
| Pan Rate | Mechanical rotation of a mounted camera to increase effective coverage | Pan rate allows the camera body to rotate in the horizontal and vertical planes. Amount of rotation and rotation speed considerations must be made based upon coverage requirements for a given installation. | Most cameras suffer motion blur, degrading image usability. Camera limit on speed must be evaluated. | |

| Parameter/ Condition | Recommended Target Metric | Comments | Limitations | Source |
|---|---|---|---|---|
| 360 $^{o}$ radial coverage | Concurrent coverage preferable to maximize probability of detection | Two solutions exist for concurrent 360$^{o}$ coverage with sufficient sighting range of 2 km. Current Scientific Corporation 8000 series (new for 2021) and the Rheinmetall with a device solution. Current Scientific Corporation has a single high-resolution rotation head and a fixed ring of LW uncooled sensors. Rheinmetall leverages two spinning lenses backed by cooled sensors. Other camera solutions require recommended minimum of 4 minimally overlapping cameras with 50$^{o}$ FOV (or more cameras with narrower FOV); exact number dependent on FOV, panning rate vs. species availability for detection, etc. Recommended pan rate <5 sec per degree | Rheinmetall system is bulky (~150 kg), requires large stable platform for mounting, is expensive, may be subject export restrictions (German manufacture). Both cameras require 6-12+ months build lead time to acquire. | Smith et al. 2020; Zitterbart et al. 2013, 2020a,b |
| # PSOs on duty during darkness/low-light | 2 PSOs increase detection probability of 360° radius from non-moving platform | For distances <~200 m, each of 2 PSOs monitor 180$^{o}$ of 360$^{o}$ coverage using handheld NVD and/or handheld IR, depending on environmental conditions at hand. For distances >200 m, 1 PSO monitor with IR camera waters >200 m, other PSO monitor on deck with handheld IR or NVD waters <200 m | Late-night monitoring is often difficult due to natural circadian rhythms. Sighting detection augmentation has high value in preventing missed detections. | |
| Distance to detection determination capability | In near real time | Can consist of built-in inclinometer and instant distance calculation capability including correction for curvature of the earth, alternatively use FOV and GPS. Most IR systems can integrate with PSO data collection software *Mysticetus* to calculate and instantly display distance to detection | Vessel motion in water can induce errors in distance estimation depending upon sea state. Motion related errors can be minimized if either the camera has (1) ability to track horizon or (2) provision of inertial reference to compensate for ship's motion | Smith et al. 2020; Zitterbart et al. 2020a,b |
| Platform stability | Stationary observation platform | Better stability provides more stable camera image and ability to observe to required distance; severe ship motion can adversely impact camera's ability to see out to required distance | Higher Beaufort sea states should be avoided if they affect platform stability. Stability loss adversely impacts image quality and ability to compute distance. | |
| Automatic image detection | False positives <90%<br>False negatives <10%<br>(Estimated values) | Proven reliability and consistency only available for Rheinmetall system; most well-developed systems are not yet commercially available. Field studies show that auto detection can out-perform PSO for select systems | | |

| Parameter/ Condition | Recommended Target Metric | Comments | Limitations | Source |
|---|---|---|---|---|
| Humidity conditions | ICAO < II | LW IR performs better in humidity than MW IR | | |
| Beaufort sea state | <5 | Empirical studies show that large whale blows can be detected at high probability with certain IR thermal camera systems up to about Bft 4 before exhibiting a decline in detection probability | | |
| Video capture and near real-time review capability | Yes | Highly desirable to allow PSOs to review images in near real-time for recognition confirmation as an event and allows for later view/archiving and reinforcing automatic detection algorithms | Video recordings must be appropriately compressed so as not to negatively affect image quality while reducing otherwise unmanageable, very large data storage requirements (e.g., 10 hr recording of RAW video requires approximately 680 GB), compression can achieve approximately 10:1 reduction in file size without negatively impacting image quality | pers. observ, M. Smultea |
| Integration with real-time PSO data collection & mitigation software | Yes | Integration allows for specific sighting events to be directly captured in data recording functionality. Data collection software should be capable of attaching segments of video (e.g. two minute snippet) to sightings for review and confirmation by PSO. Integration allows for correct recording of events and video snippet availability for reinforcing automatic detection algorithms | Local PC storage management still required over life of project. PSO need training to offload daily image capture to external hard drive. | |
| Mitigation distance display on monitor | | Improves accuracy of detection distance estimation if system performs correctly | This feature is not known to be commercially available today with consistent reliable performance at sea | |
| HD camera in addition to thermal camera | wide FOV (>25-30°) | Adds detail & shading when used simultaneously during daylight | | |

**Table 6. Recommended list of night vision and thermal devices considered to meet the minimum mitigation and monitoring needs of different distance categories with reasonable probability of detection from vessel-based platform elevations <20 m above mean sea level (ASL) based on available reviewed information (listed alphabetically within each distance category, maximum four example devices per category).[1,2]**

| Distance Range | Example Devices | Reasons for Selection | Approx. Cost (USD)[3] | Specifications | Comments |
|---|---|---|---|---|---|
| 0-200 m | FLIR MD 625 Thermal Imager | - Vessel-mounted, capable of higher elevation than observer eye height thus better FOV<br>- High pan and FOV<br>- Stabilized platform<br>- Multiple sensor resolution options available | $4,500 | -Detector Type: Thermal 640 × 480 VOx Microbolometer<br>-E-Zoom Thermal: 2×, 4×<br>-Thermal Resolution: 640 x 480 | - Recommended use is coupled with other systems to ensure adequate coverage of 200 m in diverse environmental conditions<br>- Relatively low cost<br>- Useful at ranges 200–500 m in calm sea states |
| | FLIR Ocean Scout 640 | - Handheld monocular device<br>- Lightweight<br>- Good resolution/price performance distances <200 m | $3,500 | -Detector Type: Thermal 640 x 512 VOx Microbolometer<br>-Thermal Resolution: 640 x 512<br>-Zoom: none | - Lightweight device supports observer handheld use<br>- PSOs reported preference for monocular over binoculars to minimize eye fatigue (Smultea et al. 2019)<br>- Low cost of acquisition<br>- Reported performance range <200 m (Smultea et al. 2019) |
| 201-500 m[3] | NVTS Reliant 640HD | - High pixel resolution<br>- Supports wide range of FOV options<br>- Vessel-mounted<br>- HD camera coupled to device<br>- Turnkey solutions available (monitoring/recording) | $45,000 | -Sensor Type: Uncooled LW IR FPA<br>-Resolution: 640 x 480<br>-Digital Zoom: 2X, 4X | - Sensor coupled with HD camera to support daytime or concurrent viewing |
| 501-2000 m | Current Scientific Corporation Night Navigator 2515 (uncooled) | - High pixel resolution<br>- Gyro-stabilized platform<br>- Vessel-mounted<br>- Supports wide range of FOV options<br>- Best cost to performance<br>- Mechanically gyro-stabilized platform<br>- HD camera feed coupled with device | $50,000 base price | -Spectral range: 8 – 14 µm Uncooled thermal imager<br>-Sensor type: LW IR<br>-Resolution: 640x480 pixels<br>-Zoom: 4x digital zoom | - 2515 is new design lighter weight at ~10 kg vs. 20 kg for predecessor and competitors<br>- Comparable to FLIR M400<br>- Sensor coupled with HD camera to support daytime or concurrent viewing<br>- Lighter weight simplifies handling<br>- Sensor coupled with HD camera to support daytime or concurrent viewing<br>- Comparable to Concurrent Scientific Corporation 2515 |

| Distance Range | Example Devices | Reasons for Selection | Approx. Cost (USD)[3] | Specifications | Comments |
|---|---|---|---|---|---|
| | | - Turnkey systems available with video recording/playback<br>- Newer model displays declination angle convertible to objective distance using trigonometric calculations | | | - Outright purchase price not available<br>- Sighting coverage only within immediate FOV |
| | Current Scientific Corporation 8000 360F | - High pixel resolution<br>- Supports wide range of FOV options<br>- Vessel-mounted<br>- HD camera coupled to device<br>- Turnkey solutions available (monitoring/recording)<br>- Displays declination angle convertible to objective distance using trigonometric calculations | Contact manufacturer for up-to-date quotes | - Sensor type: HD MW IR cooled thermal imager ---Resolution: 1280x1024 pixels High Definition<br>-Spectral Range: 3 -5 µm<br>-Zoom: 16x Continuous Optical Zoom | - Sensor coupled with HD camera to support daytime or concurrent viewing<br>- Comparable to Concurrent Scientific Corporation 2515 |
| | NVTS Triton Guardian EO/IR | - Military grade MW IR 640 x 480 or optional LW IR<br>- Mult-axis gyrostabilization<br>- Analytic software<br>- Can be mounted on fixed mast or temporary pedestal<br>- 360° visual scan<br>- High-resolution thermal & 4 megapixel HD visible camera<br>- Live video and event alarming<br>- Optional workstations & wireless operation<br>- Modeled thermal detection range up to 5 km<br>- Portable system deployed in two hard cases | Contact manufacturer for up-to-date quotes | - Cooled (MW IR) or uncooled (LW IR) options<br>-Thermal detection ranges up to 5 km | - When alarm event occurs, camera can automatically point to precise location of event and alerts PSO of activity<br>- For each real-time alarm, analytic screen provides a still image, looping video, and live camera system view, regardless of camera that generated alarm<br>- Incorporation of alarm querying option based on a number of user-specified metadata criteria |
| | Seiche RADES FLIR M400 Marine Thermal Camera | - High pixel resolution<br>- Mechanically gyro-stabilized platform<br>- Vessel-mounted<br>- HD camera feed<br>- Supports wide range of FOV options<br>- Mechanically gyro-stabilized platform<br>- HD camera coupled to the device<br>- Turnkey solutions available (monitor/recording) | $175/day for turnkey solutions | - Sensor Type: 640 x 480 Vox Microbolometer<br>- Resolution: High Definition up to 1080/30p<br>- Zoom: 30x Optical Zoom | - Outright purchase price not provided by manufacturer<br>- FLIR-based sensors<br>- Further development reportedly halted- Sensor coupled with HD camera to support daytime or concurrent viewing<br>- Comparable to Concurrent Scientific Corporation 2515- 2515 is new design lighter weight at ~10 kg vs. 20 kg for predecessor and competitors |

| Distance Range | Example Devices | Reasons for Selection | Approx. Cost (USD)[3] | Specifications | Comments |
|---|---|---|---|---|---|
| | | - Supports wide range of FOV options | | | - Comparable to FLIR M400 |
| **>2000 m** | Rheinmetall AIMMM | - Reported high performance<br>- High pixel resolution<br>- Mechanically gyro-stabilized platform<br>- Vessel-mounted<br>- HD camera feed<br>- Reported high performance<br>- Supports wide range FOV options<br>- HD camera coupled with device<br>- Video recording/playback | Estimated $750,000 purchase price; $10,000/ day rental | -Spectral range: 8 – 14 µm Uncooled thermal image<br>-Resolution: 640x480 pixels<br>-Zoom: 4x digital zoom | - Only known complete, single-device solution providing 360° coverage<br>- Reported to require experienced engineer to operate/maintain at sea per available info (e.g., Smith et al. 2020)<br>- Product derived from defense application<br>- Significantly more expensive than others analyzed here<br>- Product derived from defense application |

[1] Definitions: AIMMMS = Automatic Marine Mammal Mitigation system, FOV = field of view, HD = high definition, RADES = Real-time Automated Distance Estimation at Sea, USD = U.S. dollars,
[2] Devices are identified only once in their farthest distance category (to avoid repetition across distance categories) and are assumed to function well at shorter distance categories.
[3] Approximate costs as of early 2018 (pers. comm. and/or available manufacturer or reseller information).
[4] For mid-range distances (200-500 m), handheld devices were dropped from consideration due to limited FOV and reported poor performance in elevated sea states. Preference was given to mounted solutions with mechanical stabilization.
[5] For distances >500 m, all systems are based on preference for mechanically stabilized platforms.

# 6 Recommended Best-performing Device Specifications and Conditions

This section summarizes what the authors found to be the best-performing specifications and conditions of NVDs for the purposes of high-probability detection of marine mammals (particularly large whale blows) during darkness/low visibility to ensure a concurrent 360° view within ~1.5-2+ km of a typical offshore wind industry vessel in the U.S. Atlantic, as relevant to PSO mitigation and monitoring during construction, operations, and maintenance. Findings are based on (1) a search and review of available literature on previous assessments of vision-enhancing devices; (2) review of specific device specifications, and (3) modeled, expected/reported, or known performance.

## *6.1 Recommended IR/Thermal Camera Parameters*

Table 5 summarizes the authors' defined intrinsic and extrinsic parameters that should be addressed to meet the above conditions based on reviewed information. In Table 6, the authors identify examples of night vision and IR devices that appear capable of detecting cetaceans from vessels based on various distance categories, as available at the time of this report writing. Devices in Table 6 were selected from a detailed review of NVDs listed in Appendix D Summary of researched devices (listed alphabetically).

With respect to device specifications, cooled IR cameras with high-end optics are the only systems empirically, systematically, and repeatedly proven to reliably and consistently detect whale blows under the desired conditions. Recent, pending publications and theoretical modeling results have shown that use of uncooled sensors can be suitable out to ~2 km. Results of theoretical testing using standard industry and military modeling combined with non-systematic reported field results indicate that other cooled and uncooled IR systems should perform well under these conditions.

## *6.2 Effective 360° IR Camera System Solutions*

Full 360° coverage by IR camera devices (typically consisting of multiple IR devices operating simultaneously monitoring different quadrants) is considered critical to maximize detection effectiveness of marine mammals, especially for fast-moving animals such as dolphins or fin whales. Ensuring concurrent 360° coverage is especially critical when the vessel monitoring platform is stationary (as occurs during offshore wind construction pile driving) to monitor equally around the vessel.

Based on the authors' review, possible options to obtain full concurrent 360° coverage around a stationary vessel platform by an IR camera system with a high level of detection probability, and minimal risk of missing a whale blow within a reasonable given distance, include: (1) a single high-caliber, fast-rotating mounted camera with multiple sensors capable of concurrent coverage of a full 360° view (e.g., see Smith et al. 2020, Zitterbart et al. 2020a, (2) multiple mounted cameras covering separate but complimentary radii totaling the 360° view with no panning; and (3 & 4) multiple mounted cameras covering complimentary radii with Option 4 involving a panning regime characterized by low calculated probability of missing a whale blow (i.e., by the blow being out of view of the camera optics).

### 6.2.1 Option 1

Option 1 represents one of the most advanced approaches for detecting whales at sea, with supporting empirical data. The two sensor head solution has one sensor that is a fast-spinning head of >5 Hz looking for events of interest, and a second head that is also fast and designed to focus on likely recognitions for confirmation and potential identification. This latter system is a cooled LW solution that has been adopted from military applications. The system has a long lead time to acquire (it is custom built outside the U.S.) and limited commercial availability today. The dual head system has been used successfully with automatic detection software knowns as AIMMMS (Automatic Infrared-based Marine Mammal Mitigation System) for whale detection at sea.

### 6.2.2 Option 2

Option 2, like Option 1, is single-camera system (though currently in development) that has only one rotating head and a crown of LW sensors radially located around the camera base forming a crown. The high speed rotating head is designed to focus on likely detections. Option 2 also has an expected long lead time to acquire.

### 6.2.3 Option 3

Multiple uncooled and cooled IR/thermal systems are available that can be used in this approach, based on available data. When mounted, the array of camera systems provide continuous 360° coverage. Minimum recommended specifications and conditions are listed in Table 5, with examples of commercially available devices shown in Table 6. Increasing number of cameras will likely exceed the abilities of a single PSO to monitor for detection events without the support of automatic detection algorithms or multiple PSOs.

### 6.2.4 Option 4

For Option 4, any of the IR/thermal devices suitable for Option 1 or Option 2 can be used as long as they meet acceptable panning rates suited to meet the desired purpose of 360° concurrent coverage to maximize detection probability of whale detection events/blows. The optimal panning speed must be determined on a camera model configuration basis, factoring in FOV, the number of cameras being used, and prevention of motion blur. Standard formulas are available, including from manufacturers, to calculate the optimal panning speed and optics for specific camera set ups, that factor in the *in situ* expected and desired conditions and event detection parameters (detectible time and volume of detectible surface).

## *6.3 Condition-Specific Modeling Recommendations*

In summary, the authors highly recommend that condition- and device-specific theoretical modeling be undertaken prior to selection of a specific NVD/thermal device. This effort is considered necessary to better understand the viability of IR camera solutions relative to the actual expected and desired scenario/setting. We further recommend that due to rapidly changing and improving devices and features, that device manufacturer and/or distribution specialists be consulted prior to final selection of any light-enhancing or IR device to ensure that the most up-to-date model best suited to study objectives is used. For example, see FLIR's guidance for selecting a device relative to project/study objectives (http://www1.flir.com/l/5392/2011-05-03/D1P8).

# 7 References

**Acknowledgments**

We thank Daniel Zitterbart of Woods Hole Oceanographic Institute, Joseph and Julie Janson of NVTS, Sylvie Quaeyhaegens and Charline van Kesteren of Current Scientific Corp, Mark Burnett of Seiche, and Scott Kraus of the New England Aquarium for providing technical input to assist in the preparation of this paper. We thank Susan Steckler, Tammy Cloutier and Elise Cranmer of Smultea Sciences for assisting with preparation of this document.

## *7.1 Device Links*

**Table 7. Direct manufacturer links to reviewed devices and researched costs (in alphabetical order).**

| Manufacturer | Model | Link | Approx. Cost USD | Estimated Lead Time to Build/ Acquire |
|---|---|---|---|---|
| Aptomar | FLIR integration package incl software + stabilization platform | https://aptomar.com/products/sensors/flir-cameras-maritime-handheld-onshore | Contact manufacturer for up-to-date quotes | Contact manufacturer |
| ATN | PVS7-3 | https://www.atncorp.com/atn-pvs7-3-night-vision-goggles | $3,800 | 4-8 weeks |
| Current Scientific Corporation | 2526 | https://www.currentcorp.com/night-navigator-2526 | Contact manufacturer for up-to-date quotes | 3-6 months |
| Current Scientific Corporation | Night Navigator 6045 | https://www.currentcorp.com/night-navigator-3045 | $20,000 base for fixed mount solution<br><br>$80,000 - $120,000 for 360˚ pan depending on optical zoom/FOV solution | 3-6 months |
| Current Scientific Corporation | 8000 Series 360 | https://www.currentcorp.com/night-navigator-8000-360 | Contact manufacturer for up-to-date quotes | 6 months |
| FLIR | A615 | https://www.flir.com/support/products/a615#Specifications | $22,000 new | Contact manufacturer |
| FLIR | Ocean Scout 640 | https://www.flir.com/products/ocean-scout-640/ | $3,500 new | 4-8 weeks |
| FLIR | MD-Series Thermal Imagers | http://www.flir.eu/marine/display/?id=59356 | $4,200 new | 4-8 weeks |
| FLIR | M-Series thermal imagers | https://www.radioworld.ca/flir-m324xp | $11,500 new | 4-8 weeks |
| FLIR | Armasight 336 | http://www.armasight.com/thermal-imaging/thermal-weapon-sights/armasight-by-flir-predator-336-2-8x25-30-hz-thermal-imaging-weapon-sight | $4,200 new | 4-8 weeks |

| Manufacturer | Model | Link | Approx. Cost USD | Estimated Lead Time to Build/ Acquire |
|---|---|---|---|---|
| FLIR | Thermacam Ex series | http://www.flir.ca/instruments/ex-series/ | $1,500 new | 4-8 weeks |
| Night Vision 4 Less | Gen 3 AGM-HS Hand Select Night Vision Monocular | http://www.nightvision4less.com/pvs-14-mono-goggle-gen-3-agm-hs-hand-select.aspx | $4,000 new | 4-8 weeks |
| NVTS | Guardian 4 HD | https://nvtsglobal.com/product | $175,000 new ($1,350 per day rental) | 6 months |
| NVTS | Reliant 640 HD | https://nvtsglobal.com/product/reliant-640hd/ | $19.999 new | Contact manufacturer |
| Polaris Sensor Technologies, Inc | | http://www.polarissensor.com/sensing/ir-imagers/ | Component build up system, depends on configuration | Contact manufacturer |
| Rheinmetall | AIMMMS | https://www.rheinmetall-defence.com/en/rheinmetall_defence/systems_and_products/c4i_systems/reconnaissance_and_sensor_systems/automatic_marine_mammal_mitigation/index.php | ~$10,000/day rental<br>Contact manufacturer for up-to-date quotes | 6-12+ months |
| Seiche | Seiche Camera Monitoring System with RADES | http://www.seiche.com/underwater-acoustic-products/specialist-systems/thermal-imaging-hd-camera/ | $175/day rental<br>Contact manufacturer for up-to-date quotes. Alternative business models for long-term projects/ permanent installation: hardware purchase, software lease | 4-12 weeks |
| Telops | Hyper-cam FLIR integration package + detection software + stabilization platform | http://telops.com/products/hyperspectral-cameras | Est $20,000 | Contact manufacturer |
| Toyon | FLIR integration package incl software + stabilization platform | http://www.toyon.com/ | Contact manufacturer for up-to-date quotes | Contact manufacturer |
| Xenics | Gobi | https://www.xenics.com/long-wave-infrared-imagers/gobi-640-series/ | Contact manufacturer for up-to-date quotes | Contact manufacturer |

## *7.2 Additional Manufacturer Links*

- FLIR Lepton Cameras http://www.flir.com/cores/lepton/
- FLIR MD series http://www.flir.eu/marine/display/?id=59356
- FLIR Catalog http://www.flir.eu/uploadedFiles/Marine/News-Events/FLIR-Maritime-Professional-Catalogue.pdf

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# Appendix A Glossary of terminology for evaluation of infrared/thermal technology as applied in this paper

| Term | Definition |
|---|---|
| Concurrent ocean coverage | the degree of coverage provided by all cameras (Verfuss et al. 2018) |
| Observation platform height above sea level | height of eye or device (e.g., camera lens) above mean sea level (ASL). Effective sighting/visual detection distance and visible distance to the horizon are affected by this parameter as platform observation height increases, distance to the horizon also increases (Table 1). |
| Device or device form factor | any combination of sensor, optics (lens), packaging design (handheld, mounted), detection software, mechanical stabilization, and device software |
| False negative sighting | a target species enters the mitigation zone undetected and no mitigation measures are implemented |
| False positive sighting | mitigation measures taken based on false detection of a target species that did not actually exist |
| Field of view (FOV) | the extent of the area observable at any given moment within the optical view of a device, expressed as an angle in degrees |
| FLIR (Forward-Looking Infrared) cameras | uses thermal imaging sensors fit to a forward-looking IR camera that creates an image output to video by detecting IR radiation |
| Long Wave (LW) spectrum | 8 – 15 micrometer (µm) wavelength sensors obtain a passive image of objects with slight temperature differential from ambient surroundings |
| Medium Wave (MW) spectrum | 3 – 8 µm wavelength sensors are cooled and can detect targets at longer range due higher sensitivity in detecting temperature differentials. Effective in managing some atmospheric attenuation conditions. |
| Short Wave (SW) spectrum | 0.9 - 3 µm wavelength are typically used in high-temperature applications. We found no applications of use of SW IR cameras for detecting cetaceans at sea. |
| Modeling Software | Software that estimates camera effectiveness for a given camera configuration and atmospheric conditions. Options range from the Johnson Criteria (assumes no extrinsic influences) to the U.S. Army NV-IPM (factors in all influences on performance) (e.g., see Appendix B). Manufacturer quoted performance often reflects use of Johnson Criteria unless specified. |
| Planar type | operates like a digital camera, capturing the image on a two-dimensional flat plane or image sensor (Gade and Moslund 2014) |
| Rotating line scanner | a sensor mounted on a rotating gimbal giving 360˚ coverage around a vessel. Rotation speed is important to ensure capture of sighting events and reduce/eliminate false negative sightings |

| Term | Definition |
|---|---|
| Sensor image bit depth | number of bits in the captured image for analog to digital conversion. The higher the bit depth the better the image resolution. |
| Sensor sensitivity | a device's ability to measure the temperature differential between objects |
| Sensor resolution | measured in a two-dimensional plane based on the number of 'x' pixels by 'y' pixels; higher resolution (more pixels per area) results in finer detail (Smith 2008) |
| Sensor type (cooled versus uncooled) | a cooled device has far improved ability to detect thermal differences due to lower "noise" (extrinsic meteorological and oceanographic conditions) or unwanted stimuli in the sensor, though higher maintenance costs are associated with the cooling system (Dean et al. 2020) as well as higher purchase/rental costs. Uncooled sensors operate solely in LW spectra where cooled applications can work in either the LW or MW spectra. Cooled sensor-based cameras can run into military export restrictions depending on the sophistication of the device. A sensor is typically designed for either the MW or LW wavelength, not both. |
| Temperature differential | refers to differences in temperature between observed surfaces. Examples include the difference between an animal's skin temperature and the surrounding water or between a whale blow and the surrounding atmosphere. Modeling software typically assumes a 2° Kelvin differential. |

# Appendix B Definitions of the three levels of detection performance applied by the Johnson Criteria for modeling the theoretical performance of an infrared thermal imager (Sjaardema et al. 2015).[1]

| Level of Detection | Definition | Minimum Resolution (No. Pixels on Target) Required to Achieve 50% Probability for an Observer to Discriminate an Object |
|---|---|---|
| Detection | Detecting whether an object is present | 2 pixels |
| Recognition | Recognizing which class an object belongs to (e.g., a sailboat, motorboat, or person) | 8 pixels |
| Identification | Identifying descriptive details of the object, such as in the case of the military, friend or foe. | 12.8 pixels |

[1]Johnson Criteria estimates are calculated only on geometrical parameters (e.g., target size, distance, lens focal length and camera detector pixel size). Factors such as signal level, detector sensitivity, atmospheric/environmental conditions, elevation and other factors are not considered by this model. An example Johnson Criteria calculator can be found at https://www.ophiropt.com/infrared/calculator/dri-range-calculator/

# Appendix C Summary of most relevant, selected literature reviewing effectiveness of night vision technologies for detecting cetaceans, pinnipeds and sea turtles. Listed in chronological order of citation.

| Device | Manufacturer/ Model | Study Purpose | Location | Platform | Species Studied | Reported Detection Range(s) (m) | Limitations | Our Overall Qualitative Evaluation and Comments | Year of field trial/Citation (see Lit. Cited) |
|---|---|---|---|---|---|---|---|---|---|
| Night vision goggles | U.S. Army / device model not specified | Census of migrating whales; day/night whale sighting rates compared | Unimak Pass, Alaska | land | gray whales | no distance information provided | Narrow field of view and resolution problems noted | Whales were readily seen using this device | 1977-1979/ Rugh 1984 |
| Night vision goggles | Starlight Scope / goggles were likely "Gen I" goggles | Census of migrating whales; attempts were made to determine if migration rates exhibited diel patterns | Coastal California | land | gray whales | N/A | Field of view limited (<16° for the monocular scope; <40° for the goggles) | "Very few whales were seen by either system" | 1978-1979/ Reilly et al. 1980 |
| IR | Inframetrics Model 525 | | California | land | gray whales | | | This study is dated, specifics regarding devices are few. Authors concluded IR technology at the time was not ready for effective long- distance monitoring. | 1987: Greene and Chase 1987 |
| Night vision binoculars | Bushnell / ITT F5000 (Generation III) binocular | Marine mammal detections during geophysical studies | Alaskan Beaufort Sea | ship | "marine mammals" | no distance information provided | Authors noted these devices were not particularly useful | | 1988/ Richardson 1999 |
| Real-time thermal imaging system | AGEMA Infrared Systems AB, Danderyd, Sweden / Agema Thermovision 880 | "As part of a search for new detection techniques, and for obtaining information on whale surface temperatures." | Northern coast of Norway and northwest coast of Svalbard | ship | emphasis on minke whales, with four large whale species also detected -- fin, blue, humpback, and sperm whales | 70 m | "Since at distances greater than 40 m the sea surface appeared colder to the Agema 880 than it actually was, easily observable (and erroneous) infrared temperature differences between whale and sea surfaces could occur... Except for their blows and blowhole, minke whales within 20 m of the boat could not be detected because their surface temperatures were effectively those of the sea surface."; "At distances of 20 m to 150 m | Relatively good, but "strongly dependent on sea conditions, signal angle, and atmospheric interference." "Although all infrared scanning was done during daylight, this did not interfere with the infrared signal received by the scanner, due to the narrow frequency response of the unit." | 1989/ Cuyler et al. 1992 |

| Device | Manufacturer/ Model | Study Purpose | Location | Platform | Species Studied | Reported Detection Range(s) (m) | Limitations | Our Overall Qualitative Evaluation and Comments | Year of field trial/Citation (see Lit. Cited) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | from the boat, detection depended upon favorable weather and sea conditions. High swells, fog, rain, atmospheric interference, or the orientation of the surfacing whale... could reduce the infrared signal significantly." | | |
| Thermal Imaging Scope | Not identified | Seismic survey | Off Olympic Peninsula, WA | ship | pinnipeds | 1,661 m hauled out, 561 m not hauled out | Animals were detected at a farther range when hauled out than those that were not hauled out | The thermal/infrared scope used for night observations was extremely effective in sighting the warm bodies of hauled out pinnipeds, but was only effective for seeing pinnipeds which were hauled out.<br>Hauled out animals could be seen from farther distances than non-hauled out animals. | Calambokidis, J. and S. D. Osmek (1998) |
| Real-time thermal imaging system | U.S. Navy / AN/KAS-1A | | Coastal California | land | gray whales | Whale blow seen up to 8 km away | | | Perryman et al. 1999 |
| Head-mounted night vision goggle with slip-on 3X magnifier lens | ITT/5001P | Monitor harbor seal predation on Hood Canal salmonids | Hood Canal, WA | Land & bridge | harbor seals | Not provided | Distance to seal sightings using device not mentioned. | System used sunset to sunrise only in 2000. With device, observers counted maximum number of foraging seals at night and compared to daylight results. Did not find significant difference in this metric night vs. day. | 1998-2000/ London et al. 2002 |
| Bushnell UITT Night Ranger 250 binocular night vision device | | Seismic survey | Alaskan Beaufort Sea | ship | seals | 60 m | Poor detection ranges, device needs lots of light to be effective | Note effective for detecting animals at night without lots of light | Harris, R. E., et al. (2001) |
| Night vision goggles | Night Quest / Night Quest NQ220 | Test of night vision goggles to detect experimental stimuli | equatorial Pacific Ocean | ship | experimental stimuli | experimental stimuli seen at 65, 115, 165, and 215 m | Sighting rates poor at distance of 265 m | Suggests effective sighting distance in detecting floating jugs up to 200 m, and perhaps up to ~250 m or more depending on conditions | 2003/ Smultea and Holst 2003 |
| Night vision binoculars | ITT Industries / Night Quest NQ220 | | Bermuda | ship | experimental stimuli | 50-65 m; infrequently observed at 150 m | Performance tends to depend on such things as sea state and available natural/ambient light | If conditions are dark and calm, the effective sighting distance is between ~200-250 m, but during moonlit and | 2003/ Holst 2004 |

| Device | Manufacturer/ Model | Study Purpose | Location | Platform | Species Studied | Reported Detection Range(s) (m) | Limitations | Our Overall Qualitative Evaluation and Comments | Year of field trial/Citation (see Lit. Cited) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | higher sea state conditions, range closer to 65-165 m. | |
| IR binoculars | SAGEM / MATIS (Medium wavelength Advanced Thermal Imaging System) Handheld thermal imager | To field test IR binocular relative to visual and in day vs. night conditions | Mediterranean west of Sardinia and Corsica | ship | large whales, dolphins | 555-8,890 m | Effectiveness of this IR system in detecting marine mammals was strongly affected by weather conditions, ranging from excellent performance during clear and low sea-state conditions to poor performance during hazy conditions or higher sea states; instrument cooling issues; need for calibration noted | Very good (comparatively): reported consistently reliable detection up to 4.5+ nm. Good job of comparing day vs. night and visual vs. IR detections; included section on 'lessons learned and next step' | 2003/ Baldacci et al 2005 |
| FLIR IR camera | ThermaCAM E4 | Determine "thermography of the thermal energy carried in water droplets in the cetacean exhaled 'blow' as a tool for which may add objective data on respiratory activity in cetacea" | Captive animal: respiratory blow of cetacean at the Sea World facility in San Diego | laboratory study (Sea World, San Diego) | killer whale and pilot whales | Not given -- long-range detection was not study purpose | | "Thermography may have the potential to: (1) Permit remote measurement of respiratory frequency in cetacean, particularly in very cold seas; (2) add information to the decision as to whether a hunted animal is living which may be of value in the discussions on humane killing carried out by the IWC." | NA/ Butterworth 2006 |
| Long Wavelength IR sensor | ACT / MANTIS 4 (?) | | | 1) aircraft 2) land | 1) various marine mammal species; 2) humpback whales | | | | Schoonmaker et al. 2008 |
| IR (uncooled focal plane camera array) | NEC/Avio IT Technologies / ThermoTracer TH9260 | Use of IR as a means to avoid ship strikes | Japan | ship | sperm whales | up to 200 m (whales always detected within 150 m, sometimes at ranges of 160-300 m, never outside 350 m) | Images at the surface (e.g., boats and waves) complicated reliable IR detection of whales | Potential of IR camera use confirmed, but further work needed, particularly in waters of varying temperatures | 2009/ Yonehara et al. 2012 |

| Device | Manufacturer/ Model | Study Purpose | Location | Platform | Species Studied | Reported Detection Range(s) (m) | Limitations | Our Overall Qualitative Evaluation and Comments | Year of field trial/Citation (see Lit. Cited) |
|---|---|---|---|---|---|---|---|---|---|
| Long Wavelength IR (LW IR) camera | Advanced Coherent Technologies (ACT)/ EYE-5f | To assess the feasibility of detecting and counting whales from aircraft | Hawaii | aircraft | humpback whales | whales were detected from an aircraft; flights were at altitudes of 2000 and 5000 ft | | While useful, this study may not have applicability to this study. System has application for use in UAS platforms, fixed and rotary wing aircraft | 2009/ Schoonmaker et al 2011 |
| Night vision monocular, thermal imaging scopes, and spotlights | Not identified | Evaluate seasonal presence, abundance and predation activities of pinnipeds on salmonids and other fishes | Bonneville Dam tailrace (in river), OR | | California sea lions, Steller sea lions, Pacific harbor seals | | 30 hours of nighttime observations to determine if predation occurring at night. Visual observation in ambient light and with binoculars, and listening reported as more successful at detecting pinnipeds at night than night vision binoculars, monocular, scopes, thermal imaging, and high-powered spotlights. | Night vision devices reported as not very effective for study purpose. No details on models or distances. | Stansell et al. 2009 |
| 360° cooled thermal imager | Rheinmetall Defence Electronics / FIRST-Navy | Locomotive behavior and tracking of blows | Off Greenland and in Southern Ocean | ship | large whales | Ranges estimated, but not provided in paper | Gimble needed to counteract pitch of ship | System seemed capable of detecting blows -- no range information provided | 2009: Burkhardt et al. 2012 |
| IR (thermal) | Rheinmetall Defence Electronics / FIRST-Navy | Various field trials of this instrument, primarily on polar waters | Arctic, Antarctic, South Africa, Australia | ship | cetaceans | up to 5 km | Studies in subtropical waters (up to 22° C) showed detection range decreased to 90% up to 2 km, but still sufficient. | 360° scanning a plus, system has been tested in multiple trials; high detection rates. Authors reported detecting 1000s of whale blows up to 5 km in the course of multiple studies; 360° scanning and constantly gimbaled ship-mounted are a plus; observers alerted when whale blow detected | 2009+/ Zitterbart et al. 2011 |
| FLIR IR camera | FLIR Systems, Inc / Thermovision A40M | Feasibility of detecting killer whales near proposed tidal energy project | Puget Sound, Washington | land | killer whales | 52-162 m (day); 42-111m (night) | Researcher notes that killer whale fins are larger than those of other species, therefore more easily spotted with IR. At distances over 100 m, whales were primarily identified by their blows. | | 2010/ Graber 2011 |
| FLIR uncooled microbolometer | FLIR Systems, Inc / Thermovision A40M | Feasibility of detecting killer whales near proposed tidal energy facility | Puget Sound, Washington | land | killer whales | 42-162 m | Whale body versus sea surface temperatures show dependence on number of pixels per target and incidence angle | | 2010/ Graber et al. 2011 |

| Device | Manufacturer/ Model | Study Purpose | Location | Platform | Species Studied | Reported Detection Range(s) (m) | Limitations | Our Overall Qualitative Evaluation and Comments | Year of field trial/Citation (see Lit. Cited) |
|---|---|---|---|---|---|---|---|---|---|
| IR camera | Rheinmetall Defence Electronics / FirstNavy | Study of feasibility of detecting marine mammals at sea, around seismic vessels in particular, and as compared to onboard observers | Alaskan Chukchi Sea | seismic vessel | primarily pinnipeds including walrus; gray whales and one porpoise (Dall's) were seen | 50-956 m | Occurrence of false negatives; problems encountered with sea glare, haze, white caps and storage of IR images | "Showed substantial promise for detecting marine mammals at the surface during the day and especially at night". ~180 whale blows detected via IR. Dall's porpoise detectable at several hundred m, large baleen whale blows seen to 7 km. IR camera was able to detect majority of walrus surfacing <1 km some to 1.5 km. | 2010/ Weissenberger and Zitterbart 2012 |
| 360° infrared camera system | Not identified | Not identified | Alaska Chukchi Sea | ship | marine mammals | Up to 1.5 km | | Reliable and has a long range but automatic detection software would improve the system a lot | 2011/ Weissenberger, J., et al. |
| FLIR | Model M324XP | Test its application and effectiveness in detecting protected species | Hawaii | ship | sperm whales, sea turtles, seabirds | 450 m | "During periods of rain or high winds with sea spray the monitor would become hazy and difficult to observe with"; ship's infrastructure impeded ~20% of the view of the water | Not very reliable. Authors note "operating temperatures range from -25°C to +55°C... designed to withstand a 100 knot wind and has a radial view of 360°." That being said, "the PSO who detected the [faint sperm whale] blow said that they probably would not have detected it without seeing exactly where the whales were visually... and seabirds were observed visually from hundreds of meters away, [but] they were only captured on FLIR at distances less than 100 meters." | 2011/ Cameron et al. 2012 |
| FLIR thermal imaging system | FLIR Systems, Inc / FLIR model M-324XP | Assess feasibility of IR during geophysical survey monitoring | northern Mariana Islands | ship | various cetacean species | only two detections of whale spp. noted: one approx. 1,100 m, another approx. 1,800 m | | IR detections made when unaided visual observers did not see these whales | 2012/ Ellis et al. 2012 |
| Cooled IR camera system with auto detection system for whale blows | Rheinmetall Defence Electronics / FIRST-Navy combine with custom data acquisition and processing | | | | | | | Study conducted during 7 expeditions for 280 days in Arctic and Southern Ocean to evaluate an automatic, ship-based, thermographic whale detection system that continuously scans water for whale blows. Results indicated camera performance | Zitterbart et al. 2013 |

| Device | Manufacturer/ Model | Study Purpose | Location | Platform | Species Studied | Reported Detection Range(s) (m) | Limitations | Our Overall Qualitative Evaluation and Comments | Year of field trial/Citation (see Lit. Cited) |
|---|---|---|---|---|---|---|---|---|---|
| | software (Tashtego, http://tashtego.org) | | | | | | | independent of daylight, with data exhibiting almost uniform, omnidirectional detection probability within a 5-km radius from a platform height of 28.5 m. Auto detection system outperformed alerted observers based on number of detected blows and ship-whale encounters. One of first studies to successfully demonstrate efficacy of this cooled IR system at sea for detecting cetaceans based on empirical data | |
| FLIR marine camera | FLIR Systems, Inc | To explore whether thermal imaging could be used to detect Bryde's whales to avoid ship collisions; to see if smaller cetaceans (e.g., dolphins) could be detected using the same technology | New Zealand | | Bryde's whales, dolphins, seals | No specifics given | | Technology deemed successful, but no specifics are given. | Ocean Life Survey 2014, 2015 |
| IR system | Toyon Corporation / device not named | Compare IR to unaided visual observer detection rates | California | land | gray whales | whale spout detected up to 8 km m away | Field of view limited to 26˚ | Blows detected automatically using video from three IR cameras. IR and unaided visual observer detection rates were comparable. | 2014/ Sullivan 2016, Sullivan et al. 2015 |
| IR system | Seiche Measurements / device not named | | South Africa; Azores | ship | sperm whales, Risso's dolphins, pilot whales | 2 m | | | |
| Multi-mission Adaptable Narrowband Imaging System (MANTIS) | ACT / MANTIS-3 | | Hawaii | land | humpback whales | 15 km (estimated) | | | |
| Thermal-IR system | | | Newfoundland | land | humpback whales, minke | 3 km | | ≥70% of marine mammal sightings made by MMOs within 3 km of the shore-based observation site were | 2015/ Holst et al. 2017b |

| Device | Manufacturer/ Model | Study Purpose | Location | Platform | Species Studied | Reported Detection Range(s) (m) | Limitations | Our Overall Qualitative Evaluation and Comments | Year of field trial/Citation (see Lit. Cited) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | whales, harbor porpoise | | | discernible in thermal-IR imagery during periods when Beaufort sea state was ≤ 6, for all sighting cues (e.g., blow, body) and species (humpback whale, minke whales, harbor porpoise) combined. | |
| FLIR camera | FLIR Systems, Inc / FLIR A615 | To assess feasibility of detecting whales in two oceanographically diverse locations | Cook Islands and Sitka, Alaska | ship | humpback whales | Most whale blows, and some body parts, observed <150; some seen 100-150 m | Detection probabilities were similar in two oceanographically diverse (i.e., sea surface temperatures differed) locations; angle to object (as opposed to whale blow or body temperature) observed as the most important variable for detection | | Horton et al. 2017 |
| Seiche Camera Monitoring System w RADES | Seiche, Ltd. | Develop IR mounted camera system/HD camera and RADES software for detection of cetaceans | NA | vessel | large whales | Not reported | Did not report detection distances with system | Dissertation focused on development of technology. | Ladipo (2017) |
| Night vision goggles | maker not specified / Gen III | | theoretical; location not specified | theoretical; platform not specified | common dolphin, loggerhead turtle | N/A | Use of light-amplifying devices is encouraged for renewable energy mitigation work | | Theoretical, no date/ Lee and Nenadovic 2017 |
| IR system (uncooled) | Current Scientific Corporation Night Navigator 3 | Feasibility of IR camera to track whale behavior during darkness | NW Australia | research vessel | humpback whale | 2 km humpback whales; large dolphin groups 1 km, individual dolphins 500 m | None mentioned | Study conducted by K. Jenner/ Centre for Whale Research. YouTube link shows clear video of humpback whale surface behavior during darkness as observed from moving vessel using monitor linked to mounted thermal camera. Night Navigator has been used to detect whales up to 2 km from the vessel, at night, in sea states up to Beaufort 4 and with swells of up to 2 m. Dolphins were detected in large pods up to 1 km away and individual dolphins at up to 500 m from the vessel. The Australians also used | 2018/ https///www.youtube.com/watch?v=Oky0vZhp9fU |

| Device | Manufacturer/ Model | Study Purpose | Location | Platform | Species Studied | Reported Detection Range(s) (m) | Limitations | Our Overall Qualitative Evaluation and Comments | Year of field trial/Citation (see Lit. Cited) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | the equipment to detect turtles. Transects conducted from research vessel while scanning 30 ˚ either side of the bow and changing observer every 30 minutes. | |
| IR system (uncooled) | Current Scientific Corporation Night Navigator | Merinov conducted study of marine mammal behavior during darkness | Gulf of Saint Lawrence, Canada | | | | | | 2018/Merinov Testimonial #1 https://cimtchau.ca/nouvelles/une-camera-thermique-pour-reperer-les-mammiferes-marins/<br><br>Merinov Testimonial #2 https://ici.radio-canada.ca/tele/le-telejournal-est-du-quebec/site/segments/reportage/96150/merinovtechnologiecamerathermiquereperer baleines?fromApp=appInfoIos&fromMobileApp=ios |
| Seiche Camera Monitoring System with RADES | Seiche Ltd. | Monitor impacts of seismic survey of gray whales | Sakhalin Island, Russia | vessel | W Pacific gray whale | 400 m | Not relied upon for mitigation and monitoring since it had not bene previously tested in this capacity. | Three Seiche Camera Monitoring System (CMS) units were installed on-board the source vessel to provide enhanced visual coverage of near up to 360 degrees. Lead PSO reported system "provided some positive whale detections at night time." One shutdown of seismic source initiated at night due to gray whale detection by system at 400 m when visibility estimated as ~3 km. | 2018/ Tsidulko (2018) |
| Seiche Camera Monitoring System w RADES (CMS) | Seiche CMS | Mitigation and monitoring related to seismic survey | Sakhalin Island, Russia | vessel | W Pacific gray whale | not reported | | CMS recorded 49 marine mammal detections 5 detections in low-visibility directly resulting in mitigation actions involving either a delay or shut-down of seismic source. In comparison trial with marine mammal observers onboard survey vessel, 41% of detections were made by CNS operator before being visually detected by the MMO. | Seiche (2020) |

# Appendix D Summary of researched devices (listed alphabetically).

| Device | Max Effective Range (km)[1,2] | Pros | Cons |
|---|---|---|---|
| ATN PVS | 0.3[3,6] | - light weight<br>- good for close detection<br>- low cost of acquisition | -detection distance doesn't alert prior to exclusion zone |
| Current Scientific Corporation 180/360 Panoramic (uncooled sensors coupled with cooled high speed MW sensor) | 3.1 | - video tracking software<br>- fixed 52.5˚ FOV<br>- good for close detection<br>- stabilized platform<br>- HD camera for daytime<br>- Reported up to 2 km range for whale spouts | - relatively high acquisition cost<br>- modeled detection of N Atlantic right whale blow to 3.1 km and 0.8 km recognition level. Modeled detection of humpback whale blow to 1.9 km (0.5 km recognition level) using Johnson Criteria<br>- Detection modeling based on Johnson criteria<br>-MTBF maintenance off-site required after 20,000 hr of field use |
| Current Scientific Corporation Night Navigator 6065 (cooled) | 3.1 | - wide 32˚ FOV, 1.8˚ FOV available<br>- cooled system performs better in humid conditions with higher resolution than uncooled system | - MTBF maintenance off-site required after 20,000 hr of field use<br>- relatively high purchase cost; not available for rent from manufacturer<br>- modeled detection of N Atlantic right whale blow to 2.7 km and 0.7 km recognition level. Modeled detection of humpback whale blow to 1.7 km (0.4 km recognition level) using Johnson Criteria<br>- modeling does not account for environmental factors and assumes a 50% probability for an observer to discriminate an object |
| Current Scientific Corporation Night Navigator 2526 | 2.0 | - FOV 44.2 – 10.4 with optical zoom | |
| FLIR[2] A615 | 0.5[3,7] | - low, 12V, power requirement<br>- provides reliable detection of whales within range limitations | - study was at low angles negatively impacting detected temperature differential<br>- range limitation due to reduced pixel resolution |
| FLIR Ocean Scout 640 | 0.4[3,7] | - light weight<br>- good for close detection<br>- low cost of acquisition | - handheld, unstable and fatiguing to PSOs for long periods<br>- limited FOV missing events<br>- detection distance doesn't alert prior to exclusion zone<br>- range limitation due to reduced pixel resolution |
| FLIR MD 625 Thermal Imager | 0.4[3,7] | - light weight<br>- good for close detection<br>- low cost of acquisition | - detection distance doesn't alert prior to exclusion zone<br>- range limitation due to reduced pixel resolution |
| FLIR M324XP | 0.4[3,7] | -fix platform with 360$^{o}$ pan<br>-tilt +/- 90$^{o}$ | - low resolution<br>- detection distance doesn't alert prior to exclusion zone<br>- expect some blanking of view due to superstructure<br>- pan is manually controlled sightings will be missed<br>- range limitation due to reduced pixel resolution |
| FLIR Armasight Command 336 | 0.4[3,7] | - light weight<br>- good for close detection<br>- low cost of acquisition | - detection distance doesn't alert prior to exclusion zone<br>- range limitation due to reduced pixel resolution |
| FLIR Thermacam Ex series | 0.3[3,7] | - handheld lightweight<br>- small form factor | - small display limits effectiveness for seeing animals at distance<br>- low IR resolution greatly limits detection, high false negatives |

| Device | Max Effective Range (km)[1,2] | Pros | Cons |
|---|---|---|---|
| | | - product design intent for heat loss of buildings | - not directly designed for marine use |
| Gen 3 AGM-HS Hand Select Night Vision Monocular | 0.3[3,6] | - light weight<br>- good for close detection<br>- low cost of acquisition | -detection distance doesn't alert prior to exclusion zone |
| NVTS Reliant 640HD | | - low acquisition costs | - Designed for close range situational awareness coming into harbor on a small craft; it was not designed for the range, observational or stabilization requirements suited for marine mammal detection on a large vessel (pers. comm. from J. Janson/NVTS to M. Smultea, 13 December 2020) |
| NVTS Guardian 4HD MW IR (or LW IR) EO/I (uncooled or cooled options) | 2.0 | medium to long range gyro-stabilized SR camera system<br>available with Triton image recognition software<br>highly portable mobile computer system in 2 hard cases<br>built-in distance measuring tool once detected<br>ability to add and share place-markers in video<br>reported whale detection up to 5 km<br>medium size (~15-22 kg, 36 x 43 cm)<br>FOV up to 25.5° (H) x 21° (V)<br>Multi-axis gyro stabilization<br>image enhancement capability (assists in haze & low visibility conditions)<br>edge sharpness enhancement (sharpens object edges & resolution within video image)<br>optional LW IR & higher 1280 x 1024 HD<br>dual on-board processor (AKF) for dynamic inclination to estimate range to object<br>Local AGC (provides wide dynamic range of video image for camera)<br>80-90% repeatable recognition predicted for large whale blow at 2 km distance (J. Janson/NVTS, pers. comm., 27 Dec 2020)<br>93-99% probability of detection/recognition/identification modeled for human on land at 2 km distance using U.S. military model (NVTS, 2020)<br>15-300 mm f/4 20x optical zoom thermal imager<br>includes optional laser range finder<br>designed to be mounted on a fixed mast or temporary pedestal<br>event alarming<br>Mysticetus software compatibility | - the MW IR system does not perform as well as the optional LW IR system in humid conditions<br>- does not include image recognition software<br>- has not been field-tested on cetaceans<br>- modeled detection probability results limited to human target on land<br>- whale surface and blow temperature and blow size along with other environmental and camera specs needed to run efficacy modeling reports used by U.S. military |
| Polaris Sensor Technologies, Inc | 0.5[3,7] | - light weight<br>- good for close detection<br>- low cost of acquisition | - detection distance doesn't alert prior to exclusion zone<br>- range limitation due to reduced pixel resolution |

| Device | Max Effective Range (km)[1,2] | Pros | Cons |
|---|---|---|---|
| Rheinmetall AIMMMS | 3.7[3] + | - best of all units for automatic detection<br>- large FOV<br>- concurrent 360° view<br>- high rate of sighting success<br>- PSO fatigue is very low<br>- cooled LW IR system improves detection in high humidity conditions compared to MW IR<br>- cooled system provides higher resolution than uncooled system | - high cost, recent bid lease rate was more than $300K USD /month<br>- requires build lead time of approximately 6-12+ months<br>- requires onboard tech to run<br>- system detection affected by ship's response to sea state<br>- bulky (~ 159 kg)<br>- only worked on large stable vessels |
| Seiche Camera Monitoring System (Generation 1) with RADES | 2.0[3] | - high quality results within field of view<br>- sighting distance allows proactive response<br>- RADES detection software effective<br>- provides both HD visual and IR<br>- well regarded detection software<br>- manufacturer reports detecting large cetaceans to 2.5-4.0 km, small cetaceans to 1.0-1.5 km | - field studies indicate detection fails for fast moving animals and sightings outside FOV<br>- requires specialist to install<br>- multiple units required to get reliable coverage due to limited field of view<br>- relatively high daily lease rate, purchase option unknown |
| Telops | 2.0[3] | - platform solution<br>- high spectral resolution, tune to species type<br>- provides airborne platform solution | - narrow FOV<br>- adequate coverage requires multiple cameras<br>- research data missing for actual performance |
| Toyon Research Corp | Up to 5.0[4] | - light weight<br>- good for close detection<br>- low cost of acquisition | -detection distance doesn't alert prior to exclusion zone |
| Xenics | 2.0[3] | - light weight, small form factor<br>- good for close detection<br>- low cost of acquisition<br>- viable candidate for multi camera solution for 360° FOV | - research data missing for actual performance |

[1] As known for whale blows.
[2] FLIR is a prolific manufacturer of devices and sensors.
[3] Distance measured on water.
[4] Distance measured on land.
[5] Manufacturer's estimate.
[6] Research reported effective distance for sensor type for large cetaceans (Horton et al 2017).
[7] Range effectiveness in non-ideal (flat) sea-states (Horton et al 2017).

# Appendix E Literature review

One of our primary objectives was to identify specific NVDs used (or potentially used) for detecting cetaceans at sea from the literature. Therefore, we winnowed this broad collection of documents for further analysis. Those documents that did not identify a specific device (by name/model) were excluded from our focused review. In addition, several studies indicated, for example, use of 'IR devices' or 'night-vision binoculars', but did not provide sufficient detail to accommodate an evaluation of the device used.

A number of papers addressed actual or possible low-light detections of pinniped species or manatees. However, because this review is centered on at-sea detections of cetaceans, studies of hauled-out pinnipeds were excluded from our review. The same is true of studies of large terrestrial mammals. Very little information is available on detection of pinnipeds, manatees, and sea turtles at sea using night vision equipment, and what we found is summarized in Appendix D Summary of researched devices (listed alphabetically).. We also include a short review of a preliminary analysis of a sub-sample of data collected by PSOs during Ørsted G&G surveys in the U.S. Atlantic during 2018-19 by Smultea Sciences (e.g., Smultea et al. 2019). In cases where review articles cited descriptions of previous studies, we accessed the original source paper.

Some studies involved IR and other measurements in laboratory settings, whereby devices were tested for feasibility of detecting a cue from a cetacean (i.e., a blow or movement), or cetacean body part (e.g., fins or tail flukes), as differentiated from ambient or background environments. Because these devices may have application to animals in the wild, they were included in our review.

Where relevant, we emphasized studies involving devices most applicable to detecting cetaceans at sea from large vessels at ranges of <200, 201-500, 501-2000, and >2000 m. These distances correspond to current and potential agency-identified exclusion and/or monitoring zones for marine mammals associated with offshore wind development activities.

The collection of papers accessed in our general search, while excluded from our more detailed review, have been retained in separate files and can be re-visited at any time. Nonetheless, using the criteria identified above, we limited our focused review of relevant literature to a total of about 34 papers/reports (Appendix C Summary of most relevant, selected literature reviewing effectiveness of night vision technologies for detecting cetaceans, pinnipeds and sea turtles).

In general, we note that the most extensive and recent publicly available studies of IR for observing marine mammals were conducted by Zitterbart and colleagues (Weissenberger et al. 2011; Zitterbart et al. 2011, 2013, 2020a,b; Weissenberger and Zitterbart 2012; Boebel and Zitterbart 2013; Burkhardt et al. 2015; Smith et al. 2020). We note further that Verfuss et al. (2017, 2018) provided thorough reviews of technologies used during low-visibility conditions (including NVDs) and are important companion pieces to the results of our review. We also spoke with several sources who have manuscripts in preparation reviewing IR and other NVD effectiveness, including specific device models, and plan to submit them to a peer-reviewed journal in the near future. Some of this information is provided as a personal communication or unpublished data herein; other such information is considered proprietary until published and is thus not included here.

Data are sparse on specific model, specification, and cost- and at-sea effectiveness of vision-enhancing devices for detecting cetaceans during low-light/darkness conditions other than those for the higher-end device reviews identified above. Considerable field data have been collected using handheld IR and NVDs and a few mounted IR camera systems by PSOs during monitoring and mitigation of G&G survey activities associated with offshore wind development in the U.S. Atlantic since 2016. While these data have been submitted in multiple survey-, permit-, or lease-specific technical reports to BOEM and NMFS, they are not currently readily available to the public. The few exceptions are further discussed below.

In general, we found a scarcity of systematic and empirical studies on most night vision equipment. There is thus a need to test night/low-light vision devices via controlled systematic studies in regions, ideally (in the context of this paper) where offshore wind development and operations occur during low-light conditions. The authors recommend that study efforts focus on seasons and areas where sample sizes of cetacean visual detections can be maximized. One of the biggest challenges to systematic field testing and producing associated results is that higher-end, higher-resolution thermal cameras must be custom made and are relatively expensive to purchase or rent. Further, available devices and improved models are quickly updated and improved. Thus, updated results are challenging to produce on a timely basis. Reviewing available devices and data on a continuum would help identify improvements/affordability. Compilation and statistical comparisons of reported field data with data already collected using such devices during other U.S. Atlantic marine mammal monitoring is highly recommended to examine robustness and effectiveness under various conditions.

Below, we provide an overview of this assembled literature, followed by a chronology and summary of findings from each study.

## 7.4 Overview of Relevant Scientific Literature

Most studies discussed here had the express intent of evaluating a particular NVD model. However, in most cases, authors reported only on whether a particular device *was/was not* capable of detecting a cetacean and in certain conditions. That is, most studies involved primarily anecdotal observations (i.e., few or perhaps fleeting observations) – very few involved comprehensive or systematic long-term data compilations.

While this information is certainly useful, it is not amenable to making overall conclusions about the capabilities of detections by certain devices and under certain circumstances. In addition, many of the device models discussed or evaluated in the literature are no longer available or have been surpassed by more recently developed models or capabilities. Nonetheless, exercises in providing evaluations of the performance of some devices relative to others, as we have done here, is worthwhile, particularly for those devices currently or recently being used in the field to detect cetaceans at sea. Going forward, studies are needed that are specifically designed to simultaneously assess detection rates involving multiple species, comparing multiple devices, in various realistic (adverse) meteorological and oceanographic and low-light conditions, and ideally in repeatable experiments to more fully assess the capabilities of a number of devices and technologies.

Most available papers/reports we reviewed addressed the effectiveness of various devices for detecting cetaceans at sea with focus on IR devices. Relatively few tested light-enhancing (i.e., amplifying) techniques. Tests of about 10 separate IR devices and four light-amplifying devices were described or were tested in one or more studies. Each of the devices identified in these studies has been incorporated in our assessments contained herein, where sufficient detail was provided to do so.

Most studies we found and reviewed were devoted to detecting large whale species, while three each aimed to study mid- or small-sized cetacean species (Appendix C Summary of most relevant, selected literature reviewing effectiveness of night vision technologies for detecting cetaceans, pinnipeds and sea turtles). Two involved 'experimental' stimuli, e.g., steam-generated 'fake blows' in one case and inflated/floating jugs in another. An emphasis on large whales is probably related to (a) a greater likelihood of detecting a thermal image from a large-bodied animal relative to a smaller species, and (b) an emphasis on endangered species conservation. The focus on large whale species is noteworthy to our review because feasibility assessments of small cetacean detection was also sought, though studies of the latter are few relative to those for large whale species.

Available reviewed studies were conducted in various locations around the world. Most of these were conducted in the North Pacific Ocean (including waters off California, Hawaii, Washington, Alaska, and Japan; Appendix C Summary of most relevant, selected literature reviewing effectiveness of night vision technologies for detecting cetaceans, pinnipeds and sea turtles). Several studies were Arctic-based, and several in Antarctic waters; one each in waters off Australia, New Zealand, South Africa and the Cook Islands; and one in the Mediterranean Sea. Of the studies reviewed, only four occurred in waters of the North Atlantic (one in waters off Norway, three off the Canadian Maritime Provinces). We also include our own compilation and comparisons of visual detections made by PSOs using IR devices and light-enhancing NVDs from vessels during offshore wind development G&G surveys conducted by Ørsted in the U.S. North Atlantic in 2018-19 (Smultea et al. 2019). The compilation of these results illustrate the geographic scope of interest in this topic, but may also reflect either those locations where work is already being conducted (and resources/assets are already available for those locations) or where oceanographic or known mammal presence or conservation concerns are conducive to studies.

Twelve studies we reviewed were conducted from vessels, and 10 reported cetacean detection results from fixed land-based sites (Appendix C Summary of most relevant, selected literature reviewing effectiveness of night vision technologies for detecting cetaceans, pinnipeds and sea turtles). Two studies described tests from an aerial platform over marine waters and one took place in a laboratory-type setting. One study evaluated use of an IR camera during darkness and low-light conditions from a helicopter in the Atlantic (S. Kraus, New England Aquarium, pers. comm., January 2021). Clearly, the stability and predictability offered by land observation sites has advantages to the various challenges encountered at sea. For example, shore-based sites provide a consistent location and a stable elevated platform, likely more protected from elements (e.g., wind, salt spray) compared to less favorable conditions typically encountered on vessels, particularly transiting vessels. In addition, land-based studies, often conducted from vantages on the order of tens of meters above sea level, reported marine mammal detections at far greater distances than boat-based studies in which devices were typically only meters above the sea surface (see Introduction). Land-based observations, while offering reasonable platforms for feasibility studies, only have application to truly coastal species or for those species migrating close to land and generally only in certain seasons. In contrast, vessel-based observations are clearly highly desirable in the context of offshore industrial activities, requirements for marine mammal monitoring/mitigation activities, and a need to assess marine mammal presence in locations distant from shore.

Regarding light-amplifying devices, our review of the literature indicated that six devices were evaluated in six studies (one device having been evaluated in two separate studies). Four studies were conducted from vessels, two were land-based. Two of these focused on gray whales, one on bowhead whales, another on detecting dolphins and the sixth on all marine mammals detected by PSOs during G&G surveys. These studies occurred in the Arctic and in waters off California, Alaska, Bermuda, Nicaragua/Costa Rica, and the U.S. East Coast.

## *7.5 Chronology and Findings of Individual Studies*

Below, we provide a chronology of the progression of cetacean detection studies using NVDs and real-world use for monitoring and mitigation efforts for management purposes based on our literature review. The limited information available on pinnipeds and sea turtles is summarized in Appendix C Summary of most relevant, selected literature reviewing effectiveness of night vision technologies for detecting cetaceans, pinnipeds and sea turtles.

### 7.5.1 Low-light Amplifying Devices

Since at least as early as the mid-1970s, studies were conducted to assess the utility of NVDs to detect marine mammals. Limited data on gray whales migrating off the central California coastline were collected with a Starlight Scope (1975 and 1976) and night-vision goggles (1977; Reilly et al. 1980). Although not expressly indicated in the paper, goggles used in this study were likely "Gen I" goggles; this version was developed and used not long before the period of this and the following study. Night-vision goggles (U.S. Army) were used at dusk during 1978 and 1979 to count gray whales migrating past Unimak Island, Alaska (Rugh 1984). Rugh (1984) briefly commented on limitations associated with the narrow FOV (40°) and relatively low resolution of these night-vision goggles relative to their effectiveness for detecting gray whales; no information on detection distances was presented. Reilly et al. (1980) noted that the Starlight Scope had an even smaller FOV than the night-vision goggles at 16° (in contrast to 40° for the goggles), and also noted that very few whales were spotted with either of the two systems.

Greene and Chase (1987) reviewed early attempts to detect gray whales with NVDs (in this case, light-amplifying). While they noted that these NVDs were not particularly useful for studying those large whales, IR had good potential. This sentiment was echoed by Richardson (1999) regarding the inability to effectively detect marine mammals at night using a Bushnell/ITT F5000 binocular NVD (a Generation III image intensifier) during

Western Geophysical's open-water seismic program in the Alaskan Beaufort Sea during summer 1998.

Holst (2004) noted that marine mammals were rarely visually detected at night from a mitigation vessel, even with the use of NVDs; however, they did report some observation capability at close distances at night. Results of a limited systematic test during one marine mammal mitigation cruise off Bermuda, using a Night Quest NQ220 NVD, indicated that three white milk jugs tied together were generally visible out to 50 to 65 m, but were only visible to one of three observers at 150 m (on a bright night in Beaufort 4 conditions; Holst 2004). Smultea and Holst (2003) reported on a similar test conducted during L-DEO's Hess Deep seismic study in the equatorial Pacific Ocean in July 2003; all three observers could quickly and easily see white milk jugs when they were located approximately 65, 115, 165, and 215 m in Bft 3 and dark conditions, and all three observers could barely see the milk jug located at a distance of 265 m. Holst (2004) noted that results suggested that the effective sighting distance of these devices was less during moonlit nights (when light reflects off the water) with higher sea states compared with dark nights when the sea was calmer. During dark, relatively calm nights, the effective sighting distance was reported between approximately 200 and 250 m. During moonlit and higher Bft conditions, the effective sighting distance appeared to range from 65 to 165 m.

As part of a marine mammal monitoring and mitigation program during an academic geophysical seismic study off Nicaragua and Costa Rica in November-December 2004, NVDs were utilized by Holst et al. (2017a). The device (make unspecified) provided 4x magnification and an approximate 40° FOV. Of six nighttime visual detections, two were detected initially with the device, including a group of dolphins splashing at the bow.

The Noise Task Force of the Western Gray Whale Advisory Panel discussed concerns regarding night vision technology (WGWAP 2014); IR was touched on, but at the time, the technology was still being refined. One concern was that it is not just a matter of the maximum detection range of the device, but of the effective search area (i.e., the product of the area within range and the detection probability within that range, a.k.a. FOV). For example, one possibility is that some observers may find themselves scanning more slowly to compensate for the lower resolution and contrast (thus missing more cues outside their field of view); another is that observers may scan at the same rate, but only pick up the stronger cues (WGWAP 2014). Some members noted that with night vision methods, once a whale has passed through the scanned area undetected, it then has a very small chance of being detected by naked eye, even if it surfaces right in front of the vessel.

Studies suggest that detection ranges for light-amplifying devices are typically 100 to 200 m under the best conditions (e.g., no cloud cover, calm seas). When ambient light decreases due to increased cloud cover, visibility decreases dramatically and at these times observers are unable to see even 50 m with the goggles. The effective range of the more modern Generation III NVDs was estimated as a 50% detection rating being achieved at 130 m (Frankel and Vigness Raposa 2011). However, these devices also tend to have limited FOVs.

Smultea et al. (2019) conducted a summary review to identify, evaluate, and compare 15 specific vision-enhancing devices used or useful to meet U.S. regulatory requirements for marine mammal mitigation/monitoring during low-light periods of offshore wind development activities for Ørsted and Deepwater Wind in the U.S. Atlantic. Evaluation focused on cetacean detection at distances of 200, 500, and 1000 m from a vessel. Information compiled included available literature, personal communications with experts, in-field PSO results, and internet searches of equipment. Results indicated that for regulated zones <200 m radius, recently used specific hand-held IR and hand-held light-enhancing devices are considered reasonably effective. At distances of 200+ m, more expensive yet reasonably priced mounted IR devices providing automatic detection software, image stabilization, remote display, and/or delineation of mitigation zones improved objective mitigation decision-making and alleviated observer eye strain associated with handheld devices. Device performance was influenced by weather conditions (e.g., fog, rain).

### 7.5.2 Infrared

In general, IR technology has been identified as having great potential as a monitoring tool for the visual detection of marine mammals (e.g., Herata 2007; Verfuss et al. 2017, 2018; Zitterbart et al. 2013, 2020a,b). IR thermography can be used to examine various aspects of thermal physiology, diagnose injury and disease, and is a useful technique for counting warm-blooded animal populations in the wild (not only marine mammals) (McCafferty 2007; Havens and Sharp 2015). Thermal imaging technology has been applied to the identification of marine mammals from research vessels, and to help study their surface behavior (e.g., S. Kraus, New England Aquarium, pers. comm., January 2021). Warm spots include blows/exhalations and areas on the cetacean bodies where insulation is less extreme, such as flukes, rostrums, blowholes, dorsal fin/dorsal humps, and flippers, which show up clearly via IR technology (e.g., Horton et al. 2017). A cetacean's 'footprint' (i.e., the slick area left on the surface of the ocean when the cetacean flicks its tail or flukes with a downward stroke) is an area where the water surface temperature has been disturbed, and can be detected during aerial surveys using IR technology (Churnside et al. 2009). Churnside et al. (2009) also referred to this as a 'thermal track'. Recent unpublished/in preparation studies demonstrated that right whale feeding 'tracks' at the water surface were detectable with IR camera technology (S. Kraus, New England Aquarium, pers. comm., January 2021).

Greene and Chase (1987) conducted a study to assess the possibility of using an automatic detection system coupled with IR technology to detect bowhead whale blows in the Arctic. The study involved conducting experiments with captive false killer whales and free-ranging gray whales in the Santa Barbara Channel (California). Greene and Chase (1987) concluded that the IR technology at the time was not ready to facilitate long-distance, full-perimeter, 24/7 effective monitoring.

In 1989, Cuyler et al. (1992) tested the potential of IR to detect whales while conducting boat-based surveys off northern Norway and the northwest coast of Svalbard. The emphasis was on minke whales, with four large whale species also detected—fin whale, blue whale, humpback whale, and sperm whale. Detection of blows by IR was deemed more reliable than detection of the rest of the body. Detection distances were not the focus of this study; whales were studied from distances of 10 to 40 m to test the methodology.

During a trial conducted September-October 1998, the efficacy of a MilCAM-LE thermal imager with either a 50 mm or a 100 mm lens (equivalent to 2x magnification) was tested by LGL (Richardson 1999). Researchers reported that they were unable to test the unit's abilities to detect cetaceans and only one seal was observed. They reported that a thermal detector with greater resolution and, more importantly, a wider FOV, might be more effective as a means to detect marine mammals than the MilCAM-LE.

An IR system (military thermal imaging system) has been used by NMFS scientists since at least the 1990s off central California to count migrating gray whales from shore-based stations (Perryman et al. 1999). Researchers reported that gray whale blows were clearly visible in both day and night video recordings, with whales detected at distances in excess of 4 km from the survey site each year. In January 2014, NMFS tested a shore-based whale detection IR system developed by the Toyon Corporation (Sullivan 2016). Gray whale blows were automatically detected using video from three IR cameras stationed on shore at a National Oceanic and Atmospheric Administration (NOAA) research station at Granite Canyon, California; a whale blow was detected as far as 8 km away with this system (Sullivan et al. 2015).

In 2008, Schoonmaker et al. (2008) used an IR sensor deployed in a bluff-mounted configuration in Maui (Hawaii), in conjunction with a Multi-mission Adaptable Narrowband Imaging System (MANTIS). A detection range of 15 km was loosely referred to in the paper as applicable to spotting humpback whales.

Low-light detection of marine mammals was addressed as part of monitoring for the Hawaii Superferry. Dr. Joseph Mobley was lead for the marine mammal team for the project; he noted after being briefed by Current Scientific Corporation that their IR technology was "highly promising," but untested (Mobley and Uyeyama 2008). The performance of the Night Navigator IR system was evaluated by Current Scientific Corporation by using fake whale blows (hot steam emitted from a barge; Mobley and Uyeyama 2008; Current Scientific Corporation 2011 in Verfuss et al. 2017, 2018). These fake blows (3 to 6 m in height) were detected at distances of up to 2 km. Hawaii Superferry installed Current Scientific Corporation's Night Navigator 8540 system to reduce the risk of ferry collisions with humpback whales. Concerns were raised (Wilson 2008), however, and this IR system apparently was never used. Instead, observers used an unspecified make of night vision scopes and reported seeing no whales at night even though whales were seen during the day in the area and presumably might have been present (Mobley 2008; Mobley and Uyeyama 2008; Lyman et al. 2011).

In September 2009, a boat-based experiment was conducted off the Ogasawara Islands (Japan) to test the feasibility of using IR to detect sperm whales (Yonehara et al. 2012). Researchers determined that sperm whales could be reliably detected within 200 m.

Evaluation of a land-based IR camera (FLIR Thermovision) was conducted in July 2010 with future intent to monitor marine mammals for a proposed tidal energy project in Admiralty Inlet in Puget Sound, Washington (Graber 2011; Graber et al. 2011). Southern Resident killer whales were detected during twilight at ranges of 52 to 162 m and during night at 42 to 111 m. At distances over 100 m, whales were identified primarily by their blows. The scientists noted that killer whale fins are very large and therefore are an easier target for IR than other species.

Data were collected, and subsequently compared, via an IR system (FIRST-Navy) and marine mammal observers (MMOs) on an Antarctica expedition in 2012-2013 (Michel 2015). Of 955 events detected by the IR system, MMOs recorded 638 events. In addition to discrepancy in the number of detections recorded, distance estimations varied significantly between the IR system and MMOs. This was particularly noticeable for distances between 1000 m and 6000 m, with MMO estimations exceeding distances calculated from thermal images.

The most extensive studies of IR to monitor marine mammals have been conducted by Daniel Zitterbart and colleagues (Weissenberger et al. 2011; Zitterbart et al. 2011, 2013, 2020a,b; Weissenberger and Zitterbart 2012; Boebel and Zitterbart 2013; Burkhardt et al. 2015). Studies were initially focused on the Arctic and Antarctic then tested under temperate conditions between Cape Town (South Africa) and the Antarctic, off Newfoundland, Canada, and later in subtropical waters off Australia and tropical waters off Hawaii. Whales were detected at ranges up to approximately 5 km in polar, subpolar, and temperate environments (waters cooler than 16°C), under low visibility (particularly night-time), and at high sea states (up to Bft 7). Additional studies in subtropical waters found that for waters up to 22°C, the detection range was somewhat reduced (90% of sightings at a distance of up to 2 km), yet still sufficient. Zitterbart and colleagues reported that earlier findings by Baldacci et al. (2005) from the Mediterranean Sea were similar to their results. Zitterbart et al. (2013) tested the ability of thermal imaging to automatically detect cetaceans, combining a ship-mounted thermal camera with a detection algorithm to detect the thermal signature of whale blows. Zitterbart et al. (2020a,b) also compared results of a Rheinmetall IR camera and automated detection system from six different shore-based locations around the world. Comparisons included detection functions by observation platform height and Beaufort sea state (see Figure 1).

The automatic marine mammal mitigation system (AIMMMS) described by Zitterbart et al. (2013, 2020a) is not intended to operate in an unsupervised mode, but to reliably alert a marine mammal observer about the likely occurrence of any whale blow in the ship's environs, while facilitating its immediate verification and documentation. Further, operation and maintenance of the AIMMMS and Rheinmetall camera require a professional operator. The researchers determined that the number of whale observations sensed by thermal imaging was comparable to those identified by human marine mammal observers during the day. Additional studies found that this system even outperformed experienced observers (Zitterbart et al. 2020a).

Humpback whale detectability using a FLIR marine camera was studied by Horton et al. (2017) on both tropical breeding/calving ground (Rarotonga, Cook Islands) and sub-polar feeding ground (Sitka Sound, Alaska) habitats. Of the 87 blows analyzed in each study area, 32 Rarotonga blows (detected approximately 2 m above ocean surface while onboard a vessel and approximately 5-10 m above sea level from shore) and 16 Alaska blows (detected approximately 4 m above ocean surface while onboard a vessel) were imaged at distances <150 m. Of these, only 10 blows from each study area were recorded in the 100 to 150 m range. Humpback whale blows, dorsal fins, flukes and rostrums appeared as thermal anomalies of similar magnitude relative to adjacent ocean water.

Researchers with Ocean Life Survey conducted a study in Hauraki Gulf (New Zealand) in 2014 using a FLIR marine camera to explore whether thermal imaging could be used to detect Bryde's whales in enough time and at enough of a distance to avoid potential collisions with ships (Ports of Auckland 2015). A secondary component of the study was to see if smaller cetacean species, including dolphins, could be detected and identified by the same thermal imaging technology. This effort was deemed a success, though no details were provided. During a 2015 study conducted by Ocean Life Survey in the same area, thermal detection of seal species also proved successful though again, there are no specifics available. Martin Stanley expanded the thermal imaging work during 2017 to Hector's dolphins and Maui dolphins (Maui and Dolphin Defenders 2017). The plan was to use the FLIR marine camera on fishing vessels where they could improve the vessels' ability to detect the dolphins and to avoid dolphin catches in fishing gear. The first part of the study focused on identifying the dolphins in cooler ocean water conditions during October and November 2016, off both the North and South islands of New Zealand. The second stage was successfully conducted in February 2017 on the North Island, and detected the animals in their warmest water conditions, which proved the technology could be used year-round. No specific details or study reports were located, and therefore, detection ranges are unknown; this effort is therefore not included for further analyses in this report.

In 2015, Holst et al. (2017b) collected thermal-IR data at a shore-based observation site at Cape Race, Newfoundland. The researchers reported that ≥70% of marine mammal sightings made by MMOs within 3 km of the shore-based observation site were discernible in thermal-IR imagery during periods when Bft was ≤6, for all sighting cues (e.g., blow, body) and species combined (humpback whale, minke whale, harbor porpoise).

An IR system developed by Seiche Measurements was tested on a seismic vessel in South Africa and from a small vessel off the Azores (Smith n.d.). It was reported to work well from the small vessel in swells of up to approximately 2 m and in water temperatures of 17.5º C. Species detected included sperm whale, Risso's dolphin, and pilot whale. Results are not available in report form.

To study North Atlantic right whale behavior at night, New England Aquarium researchers and associates (including Scott Kraus) have tested various NVDs, including a high-resolution IR camera, a light intensifying scope, and a mirrorless, low-light digital camera (Groc 2016). In 2011, Kraus and colleagues used night vision equipment to determine the effects of rope mimics on right whale behavior during darkness on two separate nights utilizing a FLIR Thermosight ATWS Block Infrared imaging system and a U.S. Military night-vision light-intensifying scope to track and film whales. Since no skim feeding was observed by whales, the effort was suspended (Kraus and Hagbloom 2016).

Lee and Nenadovic (2017) presented an evolution of mitigation technology used in 2015 to 2017 for U.S. Atlantic offshore renewable energy sector marine mammal monitoring work. During 2015, a light-amplifying NVD (Gen III night vision goggles) was coupled with PAM, but methodology required improvement to better detect whales. This resulted in an IR flashlight being added to the PAM and NVD; however, the flashlight was determined to be ineffective and the thermal imaging camera had too small a FOV to be considered effective. Further modifications were made to include the light-amplifying NVD, PAM, and a modified handheld thermal imaging system with a more appropriate lens.

Burkhardt et al. (2015) provided a useful summary by cetacean group type and detectability by IR.

- **Large cetaceans**. So far, most large baleen whale species have been detected under temperate, subpolar, and polar conditions. A sperm whale was detected at long range (6 km) in cold waters. Humpback whale cues were discriminable in subtropical waters.
- **Medium-sized cetaceans** (3-10 m in size): This group comprises beaked whales, killer whales, and minke whales. Minke whales (including dwarf minke whales) were detected under temperate, subpolar, and polar conditions and killer whales in polar waters, while beaked whales had not yet been captured. This was attributed to a lack of opportunity rather than to their blow being too faint, as beaked whales are known for their rather cryptic behavior, long dives, and preference for regions rarely visited by Zitterbart's team.
- **Small cetaceans** (<3 m in size): Cetaceans of this size are generally detected infrequently, due mainly to a lack of opportunity. In addition, automatic detectors have so far been used primarily for detecting large whales. Bottlenose dolphins were discriminable in thermographic imaging of subtropical waters at ranges up to 1 km and Dall's porpoises in (sub)polar waters up to several hundred meters. Discriminability and detectability might increase when animals form schools, which generate a unique thermal signature that might be exploited for automatic detection by a customized detector algorithm. For example, several PSOs in the Atlantic have reported detecting groups of delphinids using IR technology out to approximately 2 km.

As noted above, thermographic monitoring only requires the whale to surface or (preferably) to blow. As the latter occurs regularly reliable surveillance is available for whales exhibiting dives not longer than 30 min, as long as the detector is sensitive enough (i.e., cryogenically cooled) to detect whales within the entire detection zone (Zitterbart et al. 2013). Burkhardt et al. (2015) noted that sperm whales (unless logging) and beaked whales may be more difficult to detect with IR due to their diving behavior (i.e., long dives); however, since these species click regularly during their dives, PAM would be considered a suitable complementary detection method.

Smultea et al. (2019) conducted a literature review and compiled field data collected by PSOs during G&G surveys conducted in the U.S. Atlantic in 2018-19 using various NVD and IR devices. Field results indicated that mounted IR cameras detected whales and delphinid groups 1-2 km away in good conditions (low sea state, minimal ambient light, clear conditions).

The detection capabilities of thermal sensors are dependent on the resolution of the image, environmental conditions (fog, rain, haze, high humidity), and background contrast (Cuyler et al. 1992; Baldacci et al. 2005; Burkhardt et al. 2015; Horton et al. 2017). Movement of the animal improves detection performance (Baldacci et al. 2005).

### 7.5.3 Literature Data Gaps

The authors' review of the available literature has indicated that a relatively small number of devices made by a limited number of manufacturers have been used in marine mammal studies. Of these, military grade (e.g., U.S. Navy; or the First Navy device made by Rheinmetall Defence Electronics) were the basis for most systematic studies conducted from vessels. The most commonly studied systems have involved non-systematic and technical reports on various light-enhancing and cooled IR devices (both handheld and mounted) for detecting marine mammals from vessels (and shore) as summarized in Appendix A Glossary of terminology for evaluation of infrared/thermal technology as applied in this paper

| Term | Definition |
|---|---|
| Concurrent ocean coverage | the degree of coverage provided by all cameras (Verfuss et al. 2018) |
| Observation platform height above sea level | height of eye or device (e.g., camera lens) above mean sea level (ASL). Effective sighting/visual detection distance and visible distance to the horizon are affected by this parameter as platform observation height increases, distance to the horizon also increases (Table 1). |
| Device or device form factor | any combination of sensor, optics (lens), packaging design (handheld, mounted), detection software, mechanical stabilization, and device software |
| False negative sighting | a target species enters the mitigation zone undetected and no mitigation measures are implemented |
| False positive sighting | mitigation measures taken based on false detection of a target species that did not actually exist |
| Field of view (FOV) | the extent of the area observable at any given moment within the optical view of a device, expressed as an angle in degrees |
| FLIR (Forward-Looking Infrared) cameras | uses thermal imaging sensors fit to a forward-looking IR camera that creates an image output to video by detecting IR radiation |
| Long Wave (LW) spectrum | 8 – 15 micrometer (μm) wavelength sensors obtain a passive image of objects with slight temperature differential from ambient surroundings |
| Medium Wave (MW) spectrum | 3 – 8 μm wavelength sensors are cooled and can detect targets at longer range due higher sensitivity in detecting temperature differentials. Effective in managing some atmospheric attenuation conditions. |
| Short Wave (SW) spectrum | 0.9 - 3 μm wavelength are typically used in high-temperature applications. We found no applications of use of SW IR cameras for detecting cetaceans at sea. |
| Modeling Software | Software that estimates camera effectiveness for a given camera configuration and atmospheric conditions. Options range from the Johnson Criteria (assumes no extrinsic influences) to the U.S. Army NV-IPM (factors in all influences on performance) (e.g., see Appendix B). Manufacturer quoted performance often reflects use of Johnson Criteria unless specified. |
| Planar type | operates like a digital camera, capturing the image on a two-dimensional flat plane or image sensor (Gade and Moslund 2014) |
| Rotating line scanner | a sensor mounted on a rotating gimbal giving 360° coverage around a vessel. Rotation speed is important to ensure capture of sighting events and reduce/eliminate false negative sightings |

| Term | Definition |
|---|---|
| Sensor image bit depth | number of bits in the captured image for analog to digital conversion. The higher the bit depth the better the image resolution. |
| Sensor sensitivity | a device's ability to measure the temperature differential between objects |
| Sensor resolution | measured in a two-dimensional plane based on the number of 'x' pixels by 'y' pixels; higher resolution (more pixels per area) results in finer detail (Smith 2008) |
| Sensor type (cooled versus uncooled) | a cooled device has far improved ability to detect thermal differences due to lower "noise" (extrinsic meteorological and oceanographic conditions) or unwanted stimuli in the sensor, though higher maintenance costs are associated with the cooling system (Dean et al. 2020) as well as higher purchase/rental costs. Uncooled sensors operate solely in LW spectra where cooled applications can work in either the LW or MW spectra. Cooled sensor-based cameras can run into military export restrictions depending on the sophistication of the device. A sensor is typically designed for either the MW or LW wavelength, not both. |
| Temperature differential | refers to differences in temperature between observed surfaces. Examples include the difference between an animal's skin temperature and the surrounding water or between a whale blow and the surrounding atmosphere. Modeling software typically assumes a 2° Kelvin differential. |

Appendix B Definitions of the three levels of detection performance applied by the Johnson Criteria for modeling the theoretical performance of an infrared thermal imager (Sjaardema et al. 2015).[1]

| Level of Detection | Definition | Minimum Resolution (No. Pixels on Target) Required to Achieve 50% Probability for an Observer to Discriminate an Object |
|---|---|---|
| Detection | Detecting whether an object is present | 2 pixels |
| Recognition | Recognizing which class an object belongs to (e.g., a sailboat, motorboat, or person) | 8 pixels |
| Identification | Identifying descriptive details of the object, such as in the case of the military, friend or foe. | 12.8 pixels |

[1]Johnson Criteria estimates are calculated only on geometrical parameters (e.g., target size, distance, lens focal length and camera detector pixel size). Factors such as signal level, detector sensitivity, atmospheric/environmental conditions, elevation and other factors are not considered by this model. An example Johnson Criteria calculator can be found at https://www.ophiropt.com/infrared/calculator/dri-range-calculator/

Appendix C Summary of most relevant, selected literature reviewing effectiveness of night vision technologies for detecting cetaceans, pinnipeds and sea turtles. As discussed previously, there are significant gaps in current data available. There is thus a need for comprehensive systematic studies to properly assess the functionality of IR and light-enhancing devices for detecting cetaceans at sea during darkness or low-light conditions.