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MITRE TECHNICAL REPORT

Technology Readiness Levels (TRL) for North Atlantic Right Whale Detection and Vessel Strike Risk Reduction

North Atlantic Right Whales (NARW) Expanding Monitoring Capabilities, Ropeless Gear Acceleration, Vessel Strike Reduction, and Program Management Development

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Table of Contents

1	Introduction	1
2	Technology Readiness Level (TRL) Overview.....	3
2.1	TRL Summary	5
2.2	Methodology	7
3	Real-time Passive Acoustic Monitoring (PAM).....	8
4	Crewed Aerial Survey	11
5	Thermal Infrared (IR) Imaging	13
6	Visual-Wavelength Optical Imaging.....	16
7	Very High-Resolution (VHR) Optical Satellite Imaging	19
8	Radar	21
9	Active Acoustic Sensing	23
10	LIDAR	25
11	Tagging.....	26
12	Environmental DNA (eDNA).....	29
13	Dimethyl Sulfide (DMS).....	31
Appendix A	One-page TRL Primer	33

1 Introduction

The North Atlantic Right Whale (NARW, *Eubalaena glacialis*) is a critically endangered species, with approximately 370 individuals remaining¹. Vessel strike has been a driver for increased mortality, particularly for calves and breeding females. The species utilizes much of the Atlantic seaboard as habitat for essential activities including foraging, calving, and annual migration, placing them near busy ports and shipping routes across both the U.S. and Canada. Current mitigation measures mainly consist of spatio-temporal management actions, such as seasonal vessel speed restrictions², which use historical information about NARW population densities to slow vessels longer than 65 feet in areas of high predicted vessel strike risk.

Seasonal vessel speed restrictions have their limitations, notably that they rely on predictions based on historical data and do not take present information into account. Furthermore, these speed restrictions impose a burden on vessels traveling through them. For these reasons, technology is seen as a promising path to enable targeted, tactical regulatory measures and vessel-specific avoidance mechanisms that could provide improved conservation outcomes with a reduced regulatory burden. “Technology” is a broad term, and many different categories can be considered for reducing vessel strike risk. The focus of this report is sensor technologies that have the capability (both potential and realized) for detecting NARWs, with a goal to increase the real-time spatial awareness of NARW locations to better inform management measures and enable mariners to take precautionary measures when warranted. Other tools that could be considered, such as predictive population density modeling and vessel modifications, are outside the scope of this report.

A variety of detection technologies are currently leveraged by the National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS) and other organizations to detect NARWs, including aerial surveys and passive acoustic monitoring (PAM). Other existing detection technologies, such as infrared (IR) cameras or active acoustic sensing, have been proposed as potential additions to this space. This report assesses the technology readiness levels (TRLs) of sensing systems for three applications: the detection of NARWs, the reduction of vessel strike risk for individual vessels (e.g., the application of technologies placed onboard a vessel), and the reduction of vessel strike risk through detection-informed dynamic management (e.g., the application of technologies offboard a vessel that are intended to observe a large region). Specific definitions and criteria for these applications are presented in Section 2.1. TRLs are assessed based on available information at the time of this report. It should be noted that some technologies can mature quickly and TRLs should be regularly re-evaluated based on new research, studies, etc.

A set of 11 technologies are covered: PAM, crewed aerial surveys, thermal/IR imaging, visual-wavelength optical imaging, very high-resolution (VHR) optical satellite imaging, active acoustic sensing, radar, light detection and ranging (LIDAR), tagging, environmental DNA (eDNA), and *in situ* dimethyl sulfide (DMS) measurements. An overview of each technology is presented, and, where applicable, a TRL is proposed and justified for each of the three applications. Brief

¹ “Report Cards,” North Atlantic Right Whale Consortium. <https://www.narwc.org/report-cards.html> (accessed Nov. 21, 2024).

² “Reducing Vessel Strikes to North Atlantic Right Whales,” NOAA Fisheries, June 2025.

<https://www.fisheries.noaa.gov/national/endangered-species-conservation/reducing-vessel-strikes-north-atlantic-right-whales> (access Nov. 22, 2024).

recommendations for next steps to increase TRL are included within justifications. In addition, a 1-page TRL primer intended for a general audience is provided in Appendix A.

There are several considerations for the implementation of these technologies that are not addressed as part of this report. The central focus is to define the maturity of a particular sensing technology to perform whale detection and reduce the risk of vessel strike, rather than assess whether the infrastructure exists for implementation to be done effectively. Widespread adoption requires more than just a high TRL technology, and the nuance and detail required to complete an assessment at this level is beyond the TRL framework. A full implementation plan would likely need to consider the cost of widespread implementation, include further development of near-real-time communication (e.g., automatic identification system (AIS) for communicating detections to, and potentially from, mariners³), and satisfy regulatory requirements in existing legislation (e.g., Marine Mammal Protection Act [MMPA], Endangered Species Act [ESA], James M. Inhofe National Defense Authorization Act (NDAA) for Fiscal Year 2023 (Public Law 117-263)). For example, some of the technologies discussed have risks of potential injury or harassment that may be problematic for current regulatory requirements, but these risks do not impact their detection performance or technical maturity. These and similar considerations are not addressed in this report.

³ P. A. McGillivray, K. Schwehr, and K. Fall, “Enhancing AIS to Improve Whale-Ship Collision Avoidance and Maritime Security,” in *IEEE Oceans*, 2009, doi: <https://doi.org/10.23919/OCEANS.2009.5422237>

2 Technology Readiness Level (TRL) Overview

TRLs are a framework that can be used to assess the maturity of a technology for a specific application. TRLs were originally developed by the National Aeronautics and Space Administration (NASA)⁴ in the 1970's for space technology planning and have since been adopted by a variety of government entities including NOAA. TRLs range from 1 to 9 and follow the development process from basic research (TRL 1) to full operational use (TRL 9). A low TRL number (1-3) suggests that the technology development is in an exploratory phase where the theoretical foundation of a technology is being established, and evidence is being gathered to test the feasibility of the technology for some specific application. Intermediate TRL numbers (4-6) suggest that prototypes are being developed, tested, and demonstrated in relevant environments. High TRL numbers (7-8) suggest that the prototype system is undergoing testing and refinement in an operational capacity. TRL 9 is reserved for technologies that are being routinely deployed and used for the intended application. An implicit assumption in the use of TRLs is that the technology development process should proceed linearly, and each TRL criteria needs to be successfully met to move forward in terms of readiness. The full definitions of each TRL used by NOAA are provided in Table 1.

⁴ J. C. Mankins, "Technology Readiness Levels, A White Paper," Washington DC, 1995.

Table 2-1. TRLs as Defined by NOAA⁵

TRL	NOAA Description
1	Basic research, experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts, without any particular application or use in view. Basic research can be oriented or directed towards some broad fields of general interest, with the explicit goal of a range of future applications
2	Applied research, original investigation undertaken in order to acquire new knowledge. It is, however, directed primarily towards a specific, practical aim or objective. Applied research is undertaken either to determine possible uses for the findings of basic research, or to determine new methods or ways of achieving specific and predetermined objectives
3	Proof-of-concept for system, process, product, service, or tool; this can be considered an early phase of experimental development; feasibility studies may be included.
4	Successful evaluation of system, subsystem, process, product, service, or tool in a laboratory or other experimental environment; this can be considered an intermediate phase of development.
5	Successful evaluation of system, subsystem process, product, service, or tool in relevant environment through testing and prototyping; this can be considered the final stage of development before demonstration begins.
6	Demonstration of a prototype system, subsystem, process, product, service, or tool in relevant or test environment (potential demonstrated).
7	Prototype system, process, product, service or tool demonstrated in an operational or other relevant environment (functionality demonstrated in near-real world environment; subsystem components fully integrated into system).
8	Finalized system, process, product, service or tool tested and shown to operate or function as expected within user’s environment; user training and documentation completed; operator or user approval given.
9	System, process, product, service or tool deployed and used routinely.

The development of radar^{6,7} is a useful example for understanding the pathway of a technology through TRLs. Radar development began with the experiments conducted by Heinrich Hertz in the 1880’s while he was a professor of physics at the Karlsruhe Polytechnic School, where he demonstrated the reflection of radio waves from metallic objects and helped to establish the underlying principles of radar (TRL 1). Christian Hülsmeier further advanced the concepts of radar specifically for preventing ship collisions. He secured a patent for his innovation and demonstrated a proof-of concept system to the German Navy, moving through TRL levels 2 and

⁵ “Readiness Levels – Office of Research Transition and Application,” NOAA, 2015. <https://orta.research.noaa.gov/support/readiness-levels> (accessed Nov. 21, 2024).

⁶ J. D. Luse, “A brief history of the use of marine radar,” *Navigation: Journal of the Institute of Navigation*, 1981.

⁷ M. L. Skolnik, “Introduction to radar systems, 3rd Ed.,” McGraw-Hill, 2001.

3. Radar was rapidly advanced by several countries in the 1930's and 1940's, including by the U.S. Navy who installed radar on several of its vessels (TRL 4-6). During this time, the term radar (RAdio Detection And Ranging) was coined. Following WWII, radar was adopted by merchant mariners and refined over the course of several decades both in terms of its technological capability and its operating guidelines (TRL 7-8). Today, the use of radar for avoiding collisions with vessels is routine and widespread and has become an established tool that is widely available from several manufacturers (TRL 9).

Specific technologies can be applied to multiple applications, and TRLs may be judged differently depending on the intended application. Radar, for example, has achieved TRL 9 for the application of avoiding collisions with ships, but is at a low maturity (TRL 3) for the application of avoiding whales because it has only been evaluated (sometimes unsuccessfully) in a limited set of environments. It is likely that some set of as-yet-unknown modifications to radar hardware or software would be required to advance its TRL for the purpose of avoiding collisions with whales.

It is important to recognize that the TRL scale is only intended to address the effectiveness of a specific technology and application relative to its *expected* performance. A mature, high-TRL technology may be expected to perform very differently under different circumstances. For example, PAM is at a high TRL for detecting NARWs but relies on whale vocalizations to make detections. If a whale is present but not vocalizing, one would not expect PAM to detect it. Similarly, an effective IR camera, mounted onboard a ship for individual vessel strike reduction, implies that a surfaced whale can be detected with enough time for the vessel to perform an avoidance maneuver. The time required to maneuver is expected to depend on vessel type, speed, and other environmental conditions. A comprehensive vessel strike risk reduction approach will require multiple high-TRL technologies working together as a system of systems to fill in gaps when certain technologies are not expected to provide actionable detection information.

It should also be noted that TRL refers to the overall technology in a given category (e.g., PAM, radar), not a specific instance. That is, TRL's are not intended to be used as a tool to compare different vendors but rather provide insight into general technology maturity.

2.1 TRL Summary

TRLs of the 11 technology categories assessed in this report are summarized in Table 2-2. The rationale for each TRL assignment is provided in the following sections (3-13). For each technology, TRLs are provided for three distinct applications:

NARW detection: the application of technologies to detect a NARW, which can then be leveraged as tools in either individual vessel and/or regional vessel strike risk reduction strategies. Many technologies that have achieved a specific TRL for detecting whales are at a lower TRL for reducing vessel strike risk reduction (e.g., satellite imagery has been shown to detect whales but requires additional development to reach the coverage rates needed for reducing vessel strike risk). It should also be noted that this category does not consider the classification of a whale as a NARW in its TRL level: detecting whales of several kinds without classifying them at the species level is sufficient if NARWs are one of the detectable whales.

Individual vessel strike risk reduction: the application of employing detection technologies on an individual vessel so that the vessel can take immediate steps to avoid a strike (e.g., slow down, turn). Achieving a high TRL for this application requires evidence that detections can occur at a sufficient distance such that these mitigation actions can be successfully executed. Further, the

various operating conditions (i.e., vessel speeds, vessel-dependent conditions such as mounting location and vessel maneuverability, expected environmental conditions) must be evaluated to fully understand the limitations of that system and under what conditions it should be expected to be effective. For example, a detection technology that has only been evaluated on a single stationary vessel will be at a lower TRL than one that has been demonstrated to make detections and provide opportunity for maneuvers across a range of vessel speeds and types. Vessel maneuvers in response to detections of whales has not been studied or documented and is a key piece to maturing any onboard detection technology for individual vessel strike risk reduction. As noted in Section 1, this category does not consider individual vessels transmitting detections broadly, as the communication infrastructure development⁸ and the regulatory considerations of individuals reporting detections are outside the scope of this report.

Risk reduction through offboard detection informed dynamic management (i.e., regional risk reduction): the application of leveraging offboard detection technologies within a specific region to inform dynamic management actions (e.g., voluntary slow zones or dynamic management areas [DMAs]) within that region to reduce vessel strike risk. This application considers technologies that provide near-real-time (within 24 hours) detection information to regulators, allowing management actions to be taken and communicated to mariners in the affected region. To achieve a high TRL for this application, a technology must be routinely used to inform dynamic management actions. It should be noted that this evaluation only considers detection technologies, not the communication methods or infrastructure that distributes management decisions.

⁸ “North Atlantic Right Whale Recovery Plan Northeast U.S. Implementation Team January 22-23, 2025, Webinar Final Summary,” NOAA Fisheries, Apr. 2025. <https://www.fisheries.noaa.gov/s3/2025-04/JAN-2025-FINAL-Meeting-Summary.pdf> (accessed August 6, 2025).

Table 2-2. TRL Assessment for Current Whale Detection Technologies

Technology	Application: NARW detection	Application: Individual vessel strike risk reduction <i>(e.g., onboard systems)</i>	Application: Regional vessel strike risk reduction <i>(e.g., offboard systems)</i>
Real-time passive acoustic monitoring (PAM)	9	3	9
Crewed aerial surveys	9	N/A	9
Thermal/ Infrared (IR) imaging	7	6	6
Visual-wavelength optical imaging	6	4	6
Very High-Resolution (VHR) optical satellite imaging	4	N/A	3
Radar	3	3	2
Active acoustic sensing	4	3	N/A
LIDAR	2	2	2
Tagging	7	N/A	3
eDNA	3	N/A	2
Dimethyl Sulfide (DMS)	2	N/A	2

2.2 Methodology

The TRL assessments described in this report were determined through a two-step process: literature review followed by discussions with key technology leaders across government and industry. The literature review established a baseline set of TRLs for the technologies listed in Section 2.1. This initial assessment was further refined based on engagements with technology experts, developers, and end users. As mentioned above, TRLs were assessed based on available information at the time of this report, and TRLs should be regularly re-evaluated based on new research, studies, implementations, etc.

3 Real-time Passive Acoustic Monitoring (PAM)

NARW's emit a variety of calls that vary seasonally and by animal [3.1], [3.2]. The acoustic waves generated by these vocalizations interact with the ocean environment in a variety of ways: they refract due to changes in sound speed and reflect or scatter at the ocean surface and seafloor. In some environments, oceanographic conditions can 'trap' these acoustic waves and cause them to travel for long distances where they can be detected by passive acoustic monitors (i.e., hydrophones). A first-order sonar equation analysis [3.3] suggests that the NARW upcalls observed and described by Parks and Tyack [3.1] could be detected at ranges of up to several km, and deeper analyses have suggested that fixed hydrophones could detect vocalizing NARWs at a few dozen km [3.4], [3.5]. An underlying assumption of the use of PAM is that the NARWs are vocalizing. NARW call rates can be highly variable and are influenced by factors such as geographic region and overall behavior [3.1], [3.2], [3.6]. For example, within the Southeast calving grounds, mother-calf pairs have extremely low call rates, making PAM challenging [3.7].

PAM sensors are generally considered as either 'archival' or real-time [3.8]. Archival PAM sensors are generally deployed for weeks to months, recording data at the sensor location, and are subsequently analyzed for a variety of scientific and regulatory purposes including assessing whale distributions as a function of geographic location and time and investigation/assessing changes in whale behavior [3.8], [3.9]. Real-time PAM sensors, which are the focus of this section, can be deployed for similar durations and must include some mechanism (e.g., cable-to-shore, cellular data modem, satellite data modem) by which to transmit information related to the detection of a whale vocalization in near-real-time (e.g., within hours).

Real-time PAM sensors can be deployed in a variety of ways. The most common deployment strategies for detecting NARWs are individual hydrophones attached to fixed buoys [3.11] and gliders [3.11], [3.12]. A common component of real-time PAM NARW detection and classification is verification by a human observer [3.12]. The Government of Canada has evaluated the use of PAM in the Gulf of St. Lawrence [3.8], [3.13] and have been using near-real time PAM detections to trigger mandatory NARW management measures for several years in the Gulf of St. Lawrence [3.14], [3.15]. Since 2020, the U.S. has used PAM detections of NARWs to trigger voluntary vessel slow zones (i.e., DMAs) [3.16]. Other sensor configurations, including hydrophone arrays [3.17], have been explored for NARW detection but have not been demonstrated in as wide a range of environments as single hydrophones.

Most real-time PAM work has been conducted for applications offboard an individual vessel, but some work has been conducted for using PAM sensors installed on vessels to detect whales. Examples include the development of a prototype software package [3.18], and the design of a prototype system used for detecting sperm whales at slow (5 kt) speeds. Technical challenges, such as flow noise encountered by the sensor during vessel movement, remain a barrier for vessel-mounted PAM systems.

NARW Detection: TRL 9

Real-time PAM sensors have been shown to accurately detect NARWs and are routinely used for that purpose in the U.S. and Canada.

Individual Vessel Risk Reduction: TRL 3

While proof-of-concept systems for onboard PAM systems have been developed [3.19], considerable work needs to be done before the technology can be implemented for individual

vessel risk reduction. To advance to a higher TRL, additional work needs to be conducted to evaluate and modify, where necessary, systems to work at higher vessel speeds and for all classes of vessels.

Regional Risk Reduction: TRL 9

Detections of NARWs using PAM sensors, such as moored buoys and glider mounted systems, are widely deployed in U.S. and Canadian waters to monitor for the presence of NARWs. This data informs analyses and vessel strike management activities in both countries. For example, near real-time NARW acoustic detections are used in the U.S. to declare voluntary dynamic slow zones (i.e., DMAs). Similarly, in Canada they are used to implement mandatory, temporary vessel speed reductions in shipping lanes.

References:

- [3.1] S. E. Parks and P. L. Tyack, "Sound production by North Atlantic right whales (*Eubalaena glacialis*) in surface active groups," *The Journal of the Acoustical Society of America*, vol. 117, no. 5, pp. 3297-3306, 2005, doi: <https://doi.org/10.1121/1.1882946>
- [3.2] L. P. Matthew and S. E. Parks, "An overview of North Atlantic right whale acoustic behavior, hearing capabilities, and responses to sound," *Marine Pollution Bulletin*, vol. 173, Dec. 2021, doi: <https://doi.org/10.1016/j.marpolbul.2021.113043>
- [3.3] R. J. Urick, *Principles of Underwater Sound*, New York: McGraw Hill, 1983.
- [3.4] C. Gervaise, Y. Simard, F. Aulanier, and N. Roy, "Optimizing passive acoustic systems for marine mammal detection and localization: Application to real-time monitoring north Atlantic right whales in Gulf of St. Lawrence," *Applied Acoustics*, vol. 178, July 2021, doi: <https://doi.org/10.1016/j.apacoust.2021.107949>
- [3.5] H. D. Hansen, M. F. Baumgartner, and C. T. Taggart, "Estimating North Atlantic right whale (*Eubalaena glacialis*) location uncertainty following visual or acoustic detection to inform dynamic management," *Conservation Science and Practice*, vol. 2, no. 10, Oct. 2020, doi: <https://doi.org/10.1111/csp2.267>
- [3.6] S. E. Parks, A. Searby, A. Celerier, M. P. Johnson, D. P. Nowacek, and P. L. Tyack, "Sound production behavior of individual North Atlantic right whales: implications for passive acoustic monitoring," *Endangered Species Research*, vol. 15, pp. 63-76, Oct. 2011, doi: <https://doi.org/10.3354/esr00368>
- [3.7] D. A. Cusano, L. A. Conger, S. M. Van Parijs, and S. E. Parks, "Implementing conservation measures for the North Atlantic right whale: considering the behavioral ontogeny of mother-calf pairs," *Animal Conservation*, vol. 22, no. 3, Oct. 2018, doi: <https://doi.org/10.1111/acv.12457>
- [3.8] S. Van Parijs *et al.*, "Management and research applications of real-time and archival passive acoustic sensors over varying temporal and spatial scales," *Marine Ecology Progress Series*, vol. 395, pp. 21–36, Dec. 2009, doi: <https://doi.org/10.3354/meps08123>.
- [3.9] G. E. Davis *et al.*, "Long-term passive acoustic recordings track the changing distribution of North Atlantic right whales (*Eubalaena glacialis*) from 2004 to 2014," *Scientific Reports*, vol. 7, Oct. 2017, doi: <https://doi.org/10.1038/s41598-017-13359-3>
- [3.10] M. F. Baumgartner and Y. Lin, "Evaluating the Accuracy and Detection Range of a Moored Whale Detection Buoy near the Massachusetts Wind Energy Area," Woods Hole (MA):

Massachusetts Clean Energy Center and U.S. Department of the Interior, Bureau of Ocean Energy Management, 2019.

[3.11] K. Indeck *et al.*, “Variation in glider-detected North Atlantic right, blue, and fin whale calls in proximity to high-traffic shipping lanes,” *Endangered Species Research*, vol. 54, pp. 191–217, Jun. 2024, doi: <https://doi.org/10.3354/esr01327>.

[3.12] M. Baumgartner *et al.*, “Slocum Gliders Provide Accurate Near Real-Time Estimates of Baleen Whale Presence From Human-Reviewed Passive Acoustic Detection Information,” *Frontiers in Marine Science*, vol. 7, Feb. 2020, doi: <https://doi.org/10.3389/fmars.2020.00100>.

[3.13] C. Gervaise, Y. Simard, F. Aulanier, and N. Roy, (2019). “Performance study of passive acoustic systems for detecting North Atlantic right whales in seaways: the Honguedo strait in the Gulf of St. Lawrence”. *Canadian Technical Report of Fisheries and Aquatic Sciences*, Ottawa, Canada: Department of Fisheries and Oceans.

[3.14] “North Atlantic right whale monitoring and surveillance activities,” Department of Fisheries and Oceans Canada, Aug. 2020. <https://www.dfo-mpo.gc.ca/fisheries-peches/commercial-commercial/atl-arc/narw-bnan/narw-science-eng.html> (accessed June 27, 2025).

[3.15] “Protecting North Atlantic right whales from collisions with vessels in the Gulf of St. Lawrence,” Transport Canada, May 2021. <https://tc.canada.ca/en/marine-transportation/navigation-marine-conditions/protecting-north-atlantic-right-whales-collisions-vessels-gulf-st-lawrence> (accessed June 27, 2025).

[3.16] “Reducing Vessel Strikes to North Atlantic Right Whales,” NOAA Fisheries, June 2025. <https://www.fisheries.noaa.gov/national/endangered-species-conservation/reducing-vessel-strikes-north-atlantic-right-whales> (accessed June 27, 2025).

[3.17] V. E. Premus, P. A. Abbot, V. Kmelnitsky, C. J. Gedney, and T. A. Abbot, “A wave glider-based, towed hydrophone array system for autonomous, real-time, passive acoustic marine mammal monitoring,” *The Journal of the Acoustical Society of America*, vol. 152, no. 3, p. 1814, Sep. 2022, doi: <https://doi.org/10.1121/10.0014169>.

[3.18] E. J. Harland and M. S. Armstrong, “The real-time detection of the calls of cetacean species,” *Canadian Acoustics*, vol. 32, no. 2, pp. 76–82, Jun. 2004.

4 Crewed Aerial Survey

Currently, crewed aerial flight surveys are among the most common methods for locating and identifying NARWs [4.1], [4.2]. Aerial surveys have several distinct advantages over ship-based surveys, particularly the ability to cover a large area quickly with minimal disturbance to surrounding wildlife [4.3]. In both the U.S. and Canada, aerial surveys are regularly conducted throughout the year along NARW habitat [4.4], [4.5], [4.6], [4.7], [4.8], operated by various institutions such as NOAA Fisheries, the New England Aquarium, HDR Inc, Transport Canada, and others. Extensive reports are available documenting the findings of these aerial surveys [4.9], [4.10].

A standard aerial survey documents the species of whale encountered and georeferenced time and location of sightings. Flights are conducted several hundred meters above sea level, with a trained observer on both sides of the aircraft [4.11]. These observers leverage photography for identification of individual animals, which aids in population monitoring. Flights are conducted during the daytime and in good weather to maximize crew safety and the probability of sighting whales [4.12]. A range of environmental conditions, including sea state, visibility, sun angle, glare, and wind, affect the probability of detection.

Camera systems mounted in the belly of the aircraft have also been used to provide additional sighting data. Moving forward, automation of these systems and improving cameras will allow for higher altitudes, greater field-of-views, and greater survey speeds for track line imaging [4.13].

NARW Detection: TRL 9

Crewed aerial surveys are conducted regularly as a means of detecting NARW and other marine mammals. These surveys are currently used for population monitoring and identification of individual NARWs. In both the U.S. and Canada, detections from historical aerial surveys have informed seasonal speed restrictions. In the U.S., these regulations, Seasonal Management Areas (SMAs), mandate that when in effect, vessels of 65 feet or longer must travel at 10 knots or less in specified areas [4.14].

Individual Vessel Risk Reduction: Not applicable

Regional Risk Reduction: TRL 9

In Canada, crewed aerial surveys are routinely conducted to control speed restrictions within dynamic shipping zones [4.13]. When NARWs are detected, mandatory speed restrictions go into effect for 15 days beginning on the day of detection. If aerial surveillance is unable to be performed due to inclement weather, a speed restriction is applied until another surveillance flight is conducted and no NARWs are detected. Within the U.S., aerial survey detections inform voluntary Right Whale Slow Zones or DMAs. NOAA will establish a DMA, for example, when sightings of three or more NARWs are made within a discrete area. For a period of 15 days after the detection, mariners are encouraged to avoid these areas or reduce speeds to 10 knots or less [4.14].

References:

[4.1] H. Johnson, D. Morrison, and C. Taggart, “WhaleMap: a tool to collate and display whale survey results in near real-time,” *Journal of Open Source Software*, vol. 6, no. 62, p. 3094, Jun. 2021, doi: <https://doi.org/10.21105/joss.03094>.

- [4.2] T. Cole, C. Khan, A. Ogilvie, C. Khan, and A. Ogilvie, “NEFSC Right Whale Aerial Survey,” *Global Biodiversity Information Facility*, Jan. 2024, doi: <https://doi.org/10.15468/bbuybm>.
- [4.3] “Aerial Survey Results for North Atlantic Right Whales in the Southeast U.S.,” *NOAA Fisheries*, Aug. 2020. <https://www.fisheries.noaa.gov/southeast/endangered-species-conservation/aerial-survey-results-north-atlantic-right-whales> (accessed June 27, 2025).
- [4.4] “OBIS-SEAMAP,” Duke.edu, 2024. <https://seamap.env.duke.edu/dataset/513> (accessed Nov. 25, 2024).
- [4.5] L. C. Ganley, S. Brault and C. A. Mayo, "What we see is not what there is: estimating North Atlantic right whale *Eubalaena glacialis* local abundance," *Endangered Species Research*, vol. 38, pp. 101-113, 2019.
- [4.6] C. W. Clark, M. W. Brown, and P. Corkeron, “Visual and acoustic surveys for North Atlantic right whales, *Eubalaena glacialis*, in Cape Cod Bay, Massachusetts, 2001-2005: Management implications,” *Marine Mammal Science*, vol. 26, no. 4, pp. 837–854, May 2010, doi: <https://doi.org/10.1111/j.1748-7692.2010.00376.x>.
- [4.7] “Aquarium scientists see one third of North Atlantic right whale population during winter/spring aerial survey season - New England Aquarium,” New England Aquarium, Jun. 19, 2023. <https://www.neaq.org/about-us/press-room/press-releases/aquarium-scientists-see-one-third-of-north-atlantic-right-whale-population-during-winter-spring-aerial-survey-season> (accessed Nov. 25, 2024).
- [4.8] L. Crowe *et al.*, “In plane sight: a mark-recapture analysis of North Atlantic right whales in the Gulf of St. Lawrence,” *Endangered Species Research*, 2021, doi: <https://doi.org/10.3354/esr01156>.
- [4.9] T. V. Cole, P. Gerrior and R. L. Merrick, "Methodologies and Preliminary Results of the NOAA National Marine Fisheries Service Aerial Survey Program for Right Whales (*Eubalaena glacialis*) in the Northeast U.S., 1998-2006," U.S. Dep. Commer., North-east Fish. Sci. Cent. Ref. Doc. 07-02, Woods Hole, MA, 2007.
- [4.10] “North Atlantic Right Whale Sighting Survey Reports,” NOAA Fisheries, Oct. 2019, <https://www.fisheries.noaa.gov/resource/document/north-atlantic-right-whale-sighting-survey-reports> (accessed June 27, 2025).
- [4.11] C. P. Fairfield and S. A. Mizroch, "Comparison of abundance estimation techniques for the western North Atlantic right whale (*Eubalaena glacialis*).," Rep. Int. Whaling Comm, 1990.
- [4.12] R. Bogucki, M. Cygan, C. B. Khan, M. Klimek, J. K. Milczek, and M. Mucha, “Applying deep learning to right whale photo identification,” *Conservation Biology*, vol. 33, no. 3, Nov. 2018, doi: <https://doi.org/10.1111/cobi.13226>.
- [4.13] “Protecting North Atlantic right whales from collisions with vessels in the Gulf of St. Lawrence,” Transport Canada, Nov. 2024. https://tc.canada.ca/en/marine-transportation/navigation-marine-conditions/protecting-north-atlantic-right-whales-collisions-vessels-gulf-st-lawrence#toc_1 (accessed Nov. 25, 2024).
- [4.14] “Reducing Vessel Strikes to North Atlantic Right Whales,” *NOAA Fisheries*, June 2025. <https://www.fisheries.noaa.gov/national/endangered-species-conservation/reducing-vessel-strikes-north-atlantic-right-whales> (accessed June 27, 2025).

5 Thermal Infrared (IR) Imaging

IR technologies detect radiated thermal energy directly generated by a source, allowing for the visualization of temperature differences from the background environment. IR has been shown to detect whales [5.1], including NARWs [5.2], by sensing the temperature difference between the ocean and the whale's body or blow, limiting detection to when whales are surfacing. It should be noted that due to similarities in blows and body features, it is challenging to use IR for whale species classification [5.3]. To make detections, IR camera images or video feeds are either monitored by a human or run through an automated detection algorithm and then validated by a human. Both the manual and automated detection capabilities of these systems have been well documented for applications both onshore [5.3], [5.4] and onboard vessels [5.2], [5.5]. Uncrewed aerial system (UAS) mounted with IR cameras have been used to study whales [5.6], [5.7], [5.8], but they have mainly been used as additional survey equipment rather than the mechanism for detection.

IR system performance is dependent on a variety of factors. Detection accuracy is greatly impacted by camera specifications (e.g., resolution, mounting stabilization, field of view, panning vs. static camera) as well as system cooling; cooled systems are less susceptible to thermal noise, increasing accuracy [5.9]. Additionally, system configuration (e.g., number of cameras used, camera mounting height) determines the detection range for a specific implementation [5.3]. Both detection accuracy and range are decreased under a variety of environmental conditions, including wind, rain, fog, and high sea state [5.1]. Under ideal conditions, studies have shown the ability to detect whales at a distance up to 3-6 km [5.1], [5.5]. However, reliable detection range can be 1 km or lower in more challenging environmental conditions [5.10]. In addition, IR detection is highly dependent on the detection procedure used. Currently used automated IR detection algorithms have high false positive rates, where birds, small vessels, and wave activity are mistaken for whales [5.1], often requiring an added step for a human to validate detections.

NARW Detection: TRL 7

IR systems have been shown to detect whales, including NARWs [5.11], in a variety of applications. While not yet routinely used like other detection technologies (e.g., PAM, crewed aerial surveys), their implementation is expected to continue to grow over time. Real-time operational testing of final systems in a wide range of environmental conditions is needed to fully evaluate performance.

Individual Vessel Risk Reduction: TRL 6

Vessel onboard IR systems have been shown to detect whales, including NARWs. However, most of these studies are conducted on a stationary or slow-moving vessel. Additional experimentation is required to determine the detection capabilities of these sensors at varying speeds and on vessels of different sizes. Beyond this, no studies have been documented regarding the ability for a vessel to make any type of detection with an onboard sensor and use that information to actively avoid a whale. A thorough analysis and testing of whale avoidance with IR cameras has the potential to help inform the development of other technologies.

Regional Risk Reduction: TRL 6

Strategically placed onshore IR systems have been proposed to inform dynamic management actions in high traffic areas close to shore. For example, the Government of Canada has been testing the use of thermal detection of NARWs in Cabot Strait, near the entrance to the Gulf of St.

Lawrence, Canada, since 2022 [5.11]. However, thermal IR detection has yet to be integrated into regional risk reduction strategies in either the U.S. or Canada. Detection range remains a challenge for these shore-based systems; a whale must be close to shore and within the IR system's field of view for a blow or exposed body part to be detected. Further testing is needed to define the range at which these systems can reliably detect whales under varying conditions, as well as demonstration that these detections can be transmitted in real-time for use in dynamic management.

References:

[5.1] D. P. Zitterbart *et al.*, “Scaling the Laws of Thermal Imaging–Based Whale Detection,” vol. 37, no. 5, pp. 807–824, May 2020, doi: <https://doi.org/10.1175/jtech-d-19-0054.1>.

[5.2] L. Baille and D. Zitterbart, “Effectiveness of surface-based detection methods for vessel strike mitigation of North Atlantic right whales,” *Endangered Species Research*, 2022, doi: <https://doi.org/10.3354/esr01202>.

[5.3] S. Richter *et al.*, “Coastal marine mammal conservation using thermal imaging-based detection systems,” *bioRxiv (Cold Spring Harbor Laboratory)*, Aug. 2023, doi: <https://doi.org/10.1101/2023.08.25.554754>.

[5.4] J. Graber, J. Thomson, B. Polagye, and A. Jessup, “Land-based infrared imagery for marine mammal detection,” *Proceedings of SPIE, the International Society for Optical Engineering/Proceedings of SPIE*, Jan. 2011, doi: <https://doi.org/10.1117/12.892787>.

[5.5] D. P. Zitterbart, L. Kindermann, E. Burkhardt, and O. Boebel, “Automatic Round-the-Clock Detection of Whales for Mitigation from Underwater Noise Impacts,” *PLoS ONE*, vol. 8, no. 8, p. e71217, Aug. 2013, doi: <https://doi.org/10.1371/journal.pone.0071217>.

[5.6] T. W. Horton, N. Hauser, S. Cassel, K. F. Klaus, T. Fettermann, and N. Key, “Doctor Drone: Non-invasive Measurement of Humpback Whale Vital Signs Using Unoccupied Aerial System Infrared Thermography,” *Frontiers in Marine Science*, vol. 6, Jul. 2019, doi: <https://doi.org/10.3389/fmars.2019.00466>.

[5.7] G. Lonati, D. Zitterbart, C. Miller, P. Corkeron, C. Murphy, and M. Moore, “Investigating the thermal physiology of critically endangered North Atlantic right whales *Eubalaena glacialis* via aerial infrared thermography,” *Endangered Species Research*, 2022, doi: <https://doi.org/10.3354/esr01193>.

[5.8] C. Burke, M. Rashman, S. Wich, A. Symons, C. Theron, and S. Longmore, “Optimizing observing strategies for monitoring animals using drone-mounted thermal infrared cameras,” *International Journal of Remote Sensing*, vol. 40, no. 2, pp. 439–467, Jan. 2019, doi: <https://doi.org/10.1080/01431161.2018.1558372>.

[5.9] U. K. Verfuss *et al.*, “Comparing methods suitable for monitoring marine mammals in low visibility conditions during seismic surveys,” *Marine Pollution Bulletin*, vol. 126, pp. 1–18, Jan. 2018, doi: <https://doi.org/10.1016/j.marpolbul.2017.10.034>.

[5.10] D. P. Zitterbart, “Offshore thermal imaging whale detection test in Canadian waters: Final Research Performance Progress Report,” Office of Naval Research, 2022. <https://apps.dtic.mil/sti/trecms/pdf/AD1207369.pdf>

[5.11] “Protecting North Atlantic right whales from collisions with vessels in the Gulf of St. Lawrence,” Transport Canada, May 28, 2021. <https://tc.canada.ca/en/marine->

transportation/navigation-marine-conditions/protecting-north-atlantic-right-whales-collisions-vessels-gulf-st-lawrence

6 Visual-Wavelength Optical Imaging

Electro-optical (EO) cameras convert light into electrical signals. While a wide range of technologies fall under the general EO camera category, the focus of this evaluation is the use of visual-wavelength cameras, hereafter referred to as visual cameras, those that operate in the visible region of the electromagnetic spectrum. It should be noted that IR cameras are also a type of EO imaging, but they operate in the IR spectrum band and are addressed separately (see Section 5). In whale detection applications, particularly for vessel-based or shore-based platforms, IR cameras and visual cameras are often used together in the same system. IR imaging can typically provide higher contrast images and video compared visual cameras because it relies on temperature differences rather than variations in reflected ambient light. There are several studies utilizing detection systems where a visual camera is leveraged to aid in visual confirmation of IR data, support species identification, or determine animal range [6.1], [6.2], [6.3]. Although less prevalent, there are a few documented examples of data from a visual camera being used for initial whale detection. For instance, a study presenting the use of artificial whale blow leverages a combined visual and IR system, where information from both cameras were independently used to detect artificial blows during testing [6.4]. The performance of visual cameras is impacted by environmental conditions (e.g., fog, rain, sea state) and system configuration (e.g., number of cameras used, camera mounting height) [6.2]. Visual cameras are highly susceptible to reflectivity and glare, where excess reflected light can elevate background illumination, making it more challenging to distinguish a whale from the surrounding ocean [6.3].

Both the U.S. and Canada have used visual cameras mounted on aerial systems, either uncrewed (i.e., UAS) or crewed (i.e., traditional aerial survey), for NARW research, mainly as a tool to supplement existing monitoring efforts [6.5]. During uncrewed monitoring operations, the UAS will fly over the desired region to either record video and images for post-flight processing or transmit this information in real-time back to an operator. Visual cameras mounted on small UASs, which are often human launched from vessels or land, have been used to photograph whales, including NARWs, to assess a variety of health factors [6.6]. However, the effectiveness of small UASs is limited by the range, speed, endurance, and payload capacity, decreasing their applicability to vessel strike reduction applications. Visual cameras mounted on larger UASs provide a promising path for longer range and increased endurance compared to their smaller counterparts. Since 2018, Transport Canada's Remotely Piloted Aircraft System (RPAS) project has been testing large UAS technology with mounted visual cameras to aid in aerial surveillance of NARWs within Canadian waters [6.7]. As part of this ongoing effort, they have been investing in artificial intelligence (AI) to enable automated detection of whales, specifically NARWs, in near-real time [6.8]. It should also be noted that visual cameras mounted in the belly of crewed aircraft have also been explored for improved aerial survey capabilities [6.7]. Moving forward, automation of visual camera systems will allow for improved performance for both crewed and uncrewed aerial monitoring applications.

NARW Detection: TRL 6

UAS-mounted visual cameras have been used for a variety of NARW research and monitoring activities [6.5], [6.6]. The use of these cameras on large UASs shows promise for larger scale monitoring, but additional development is needed into automated detection tools, including a more robust training set for AI-based detection algorithms.

Individual Vessel Risk Reduction: TRL 4

There are minimal examples of visual camera data used to perform vessel-based whale detections [6.4]. While prototype systems exist, there is little information available regarding their performance for different vessel types, speeds, or environmental conditions. To advance the use of visual camera-based detection, further work is needed to demonstrate their performance as standalone detection modalities. Further, additional training data is needed to develop detection algorithms specifically for visual whale detection, including information from NARWs.

Regional Risk Reduction: TRL 6

As part Transport Canada's RPAS project, detections from uncrewed UAS-mounted visual cameras were included as part of the National Aerial Surveillance Program [6.9], supplementing existing crewed aerial surveys. While detections from these UAS test flights could trigger dynamic management actions specifically in Canada, they are not yet standard practice. Further work is needed to establish the protocols for UAS-mounted visual cameras in both the U.S. and Canada to routinely deploy this technology for regional vessel strike risk reduction. This includes demonstrations that images or video from these systems can be analyzed in near-real time for detections, either with a human-in-the-loop or with automated detection.

References:

- [6.1] A. Baldacci, M. Carron, and N. Portunato, "Infrared detection of marine mammals," NATO Undersea Research Centre, 2005.
- [6.2] S. Richter, H. Yurk, E. Chmelnitsky, N. Serra, P. D. O'Hara, and D. Zitterbart, "Coastal Marine Mammal conservation using thermal imaging-based detection systems," bioRxiv, 2023.
- [6.3] L. Baruwa, "Remote High-Definition Visual Monitoring of Cetaceans from offshore vessels and platforms," Ph.D. dissertation, University of Bath, 2017. Available: https://purehost.bath.ac.uk/ws/portalfiles/portal/187950206/Remote_High_Definition_Visual_Monitoring_of_Cetacean_Final_report_image_rmoved_.pdf (accessed Aug. 7, 2025).
- [6.4] R. S. Easton, J. C. Prisco, J. J. Everson, J. E. Riedel, and Y. M. Randall, "Using a Mechanical Whale to Test Automatic Whale Blow Detection with Applications to Offshore Wind Development," Offshore Technology Conference, May 2024, doi: <https://doi.org/10.4043/35428-MS>.
- [6.5] K. Luciano, "New Drone Technology is Taking Flight in Right Whale Research - New England Aquarium," New England Aquarium, Aug. 2024. <https://www.neaq.org/new-drone-technology-is-taking-flight-in-right-whale-research/> (accessed June 27, 2025).
- [6.6] J. D. Stewart et al., "Decreasing body lengths in North Atlantic right whales," *Current Biology*, vol. 31, no. 14, Jun. 2021, doi: <https://doi.org/10.1016/j.cub.2021.04.067>.
- [6.7] "Protecting North Atlantic right whales from collisions with vessels in the Gulf of St. Lawrence," Transport Canada, <https://tc.canada.ca/en/marine-transportation/navigation-marine-conditions/protecting-north-atlantic-right-whales-collisions-vessels-gulf-st-lawrence> (Access July 9, 2025).
- [6.8] W. Mackenzie, "AI-Integrated Multispectral Sensor Aids Whale Detection in Canada," *Ocean Science and Technology*, Oct. 2024. <https://www.oceansciencetechnology.com/news/ai-integrated-multispectral-sensor-aids-whale-detection-in-canada/> (Accessed July 9, 2025).

[6.9] “Backgrounder: Protecting North Atlantic Right Whales,” Transport Canada, <https://tc.canada.ca/en/backgrounder-protecting-north-atlantic-right-whales-0> (Access July 9, 2025).

7 Very High-Resolution (VHR) Optical Satellite Imaging

Low-earth orbit (LEO) satellites equipped with very high-resolution (VHR) electro-optical (EO) visual-wavelength sensors can be used to collect images of the earth's surface. Satellite imagery has been proposed as a method of whale detection that can be leveraged to supplement existing survey methods in regions outside of currently monitored areas [7.1]. Several studies have shown the use of satellite images to detect a variety of whale species [7.2], [7.3], including NARW [7.1] [7.4]. Once images are collected, whale detection can be done either manually or using automated detection algorithms. Automated detection is currently limited by the lack of available training data, and recent studies have leveraged images from aerial surveys for training machine learning (ML) models [7.5], [7.6]. Whale species classification from these images is currently a manual process, and automation requires robust training sets of different whale species [7.6].

There are a variety of commercially available satellite imagery options that are applicable for whale detection. For example, the WorldView-3 satellite, which has a 0.3 m resolution, has already been leveraged to perform satellite whale detection studies [7.3], [7.6]. However, while satellite imagery is available commercially, there are still a number of factors limiting its use and effectiveness. Satellite image quality is limited by cloud cover, angle with respect to the earth surface, sun illumination, and camera resolution [7.7]. In addition, coverage is restricted by the number of available satellites, their orbits, sensor field-of-view, pointing scheme, daylight, and weather. Further, satellite images are expensive [7.7], and there is often a significant time delay in receiving data, limiting real-time applications.

NARW Detection: TRL 4

The use of VHR satellite imagery has been demonstrated to be able to detect whales, including NARWs. However, locating whales in satellite images requires significant manual evaluation and often relies on prior knowledge of whale distribution. Further work is required on automated detection to improve feasibility, including building up more robust training sets (e.g., number of images, images taken in different sea state conditions). This is critical for NARW detection because they are less distinguishable from the surrounding ocean than other species due to their body coloration, a challenge that is well documented for the use of satellite imagery to detect southern right whales [7.8], [7.9].

Individual Vessel Risk Reduction: Not applicable

Regional Risk Reduction: TRL 3

Although satellite imagery has been demonstrated for detection, significant hurdles remain to implement these detections for vessel strike risk reduction. Classifying detected whales as NARW, particularly in areas where other whale species are co-occurring, is challenging. In addition, satellite coverage is fundamentally limited. Most available satellites have limited field of view and infrequent revisit rates (e.g., less than once per day); poor weather (e.g., cloud cover) further impacts the efficacy of these systems.

References:

[7.1] M. Hodul *et al.*, "Individual North Atlantic right whales identified from space," *Marine Mammal Science*, Sep. 2022, doi: <https://doi.org/10.1111/mms.12971>.

- [7.2] H. C. Cubaynes, P. T. Fretwell, C. Bamford, L. Gerrish, and J. A. Jackson, “Whales from space: Four mysticete species described using new VHR satellite imagery,” *Marine Mammal Science*, vol. 35, no. 2, pp. 466–491, Oct. 2018, doi: <https://doi.org/10.1111/mms.12544>.
- [7.3] B. Charry, E. Tissier, J. Iacozza, M. Marcoux, and C. A. Watt, “Mapping Arctic cetaceans from space: A case study for beluga and narwhal,” *PLOS ONE*, vol. 16, no. 8, p. e0254380, Aug. 2021, doi: <https://doi.org/10.1371/journal.pone.0254380>.
- [7.4] C. B. Khan *et al.*, “A Biologist’s Guide to the Galaxy: Leveraging Artificial Intelligence and Very High-Resolution Satellite Imagery to Monitor Marine Mammals from Space,” *Journal of Marine Science and Engineering*, vol. 11, no. 3, Mar. 2023, doi: <https://doi.org/10.3390/jmse11030595>
- [7.5] E. Guirado, S. Tabik, M. L. Rivas, D. Alcaraz-Segura, and F. Herrera, “Whale counting in satellite and aerial images with deep learning,” *Scientific Reports*, vol. 9, no. 1, Oct. 2019, doi: <https://doi.org/10.1038/s41598-019-50795-9>.
- [7.6] A. Borowicz *et al.*, “Aerial-trained deep learning networks for surveying cetaceans from satellite imagery,” *PLOS ONE*, vol. 14, no. 10, p. e0212532, Oct. 2019, doi: <https://doi.org/10.1371/journal.pone.0212532>.
- [7.7] C. Höschle, H. C. Cubaynes, P. J. Clarke, G. Humphries, and A. Borowicz, “The Potential of Satellite Imagery for Surveying Whales,” *Sensors*, vol. 21, no. 3, p. 963, Feb. 2021, doi: <https://doi.org/10.3390/s21030963>.
- [7.8] H. C. Cubaynes, P. T. Fretwell, C. Bamford, L. Gerrish, and J. A. Jackson, “Whales from space: Four mysticete species described using new VHR satellite imagery,” *Marine Mammal Science*, vol. 35, no. 2, Apr. 2019, doi: <https://doi.org/10.1111/mms.12544>
- [7.9] P. T. Fretwell, I. J. Staniland, and J. Forcada, “Whales from Space: Counting Southern Right Whales by Satellite,” *PLOS One*, vol. 9, no. 2, Feb. 2014, doi: <https://doi.org/10.1371/journal.pone.0088655>

8 Radar

Radar systems emit a beam of electromagnetic waves from a transmit aperture (or antenna). Any targets intersecting this beam reflect or scatter the waves back to the radar receiver, where they are detected and displayed. Radar is commonly used on marine vessels for safety of navigation, helping to avoid collisions with other vessels and providing a navigation aid to pilots in narrowly constrained waterways. The radar antennas found on marine vessels are typically constructed to form a narrow beam, defining the radar's angular resolution. This antenna is then mechanically scanned to provide a 360° view of targets on or near the water surface surrounding the vessel. However, scattered returns from signals of interest can be obscured by unwanted returns, known as clutter (e.g., returns from wind-waves, spray, and rain).

For the purpose of avoiding collisions with other vessels, radar has undergone a lengthy development process and has been at TRL 9 for many decades. However, few experiments have been conducted to test the efficacy of radar for the application of detecting whales with radar. DeProspero et al. [8.1] described confirmed radar returns from a humpback whale at a range of 8 km and tracks from Stenella dolphins at ranges of up to 700 m. Follow-on work using an X-band commercial radar aboard the NOAA Ship McArthur II was less successful in detecting and tracking marine mammals, with the results attributed to too many false alarms and a low-pulse-length resolution setting on the radar system [8.2]. McCann and Bell [8.3] successfully detected killer whales at approximately 1 km range using shore-based X-band radar. They identified several beneficial circumstances of their experiment, including that the whales were breaching the surface with their full bodies and were oriented broadside to the radar, both of which contribute to a large radar cross-section (i.e., strong radar return). Although McCann and Bell [8.3] demonstrated successful whale tracks, they concluded that more work was needed to catalogue radar signatures from a wide range of whale species and behaviors. It is possible that modifications to radar hardware and/or filtering techniques could increase the probability of detecting whales while reducing false alarms, such as the fully polarimetric radar and associated processing suggested by Anderson and Morris [8.4].

NARW Detection: TRL 3

Although proof-of-concept systems have been developed for detecting whales using radar [8.1], [8.2], [8.3], evaluations of these systems in small experiments have had mixed results. Further development is needed to tailor existing radar technology to reliably detect whales, in addition to specific demonstrations that focus on NARWs.

Individual Vessel Risk Reduction: TRL 3

Proof-of-concept systems aboard vessels have been tested, with mixed results. Additional assessment is needed for different vessel size classes with consideration given to achievable radar ranges and vessel maneuvering should a detection be made.

Regional Risk Reduction: TRL 2

Some work has been conducted using shore-based radar that could potentially aid a vessel strike risk reduction at the regional level, but a proof-of-concept system/process for doing this at meaningful ranges (e.g., for straits that are 10's of km wide) has not yet been developed.

References:

- [8.1] D. DeProspero, J. Mobley, W. Hom and M. Carron, "Radarbased detection, tracking and speciation of marine mammals from ships," Arete Associates Project Report, 2005.
- [8.2] C. P. Forsyth, "Radar Detection of Marine Mammals," Arete Associates, Arlington, 2011.
- [8.3] D. L. McCann and P. S. Bel, "Observations and tracking of killer whales (*Orcinus orca*) with shore-based X-band marine radar at a marine energy test site," *Marine Mammal Science*, vol. 33, no. 3, pp. 904-912, Apr. 2017, doi: <https://doi.org/10.1111/mms.12395>
- [8.4] S. Anderson and J. T. Morris, "On the detection of marine mammals with ship-borne polarimetric microwave radar," in *IEEE/MTS Oceans*, Sydney, 2010, doi: 10.1109/OCEANSSYD.2010.5603942

9 Active Acoustic Sensing

Active acoustic sensing refers to sensors which transmit pulses of sound into the water and then measure/analyze a reflected or scattered wave from an object to gather information about that object. The type of information gathered may vary from system to system but commonly includes the location of the object (e.g., range and bearing) relative to the acoustic sensor and the object type (e.g., a whale). In general, the ability of an active acoustic sensor to detect a whale depends on system-dependent parameters (e.g., source level, transmitter and receiver directivity, operating frequency), the acoustic scattering properties of the target (e.g., target size and composition), and the environment (e.g., ambient noise and reverberant properties of the ocean volume and surfaces, ocean temperature and salinity). In general, lower frequency systems with higher source strengths and higher directivities perform better than the converse for whale detection applications. More complete descriptions of these systems can be found in a variety of texts including [9.1], [9.2], [9.3].

Published reports of active acoustic sensors that have been used for the purposes of detecting whales have all been from monostatic (i.e., co-located projector and receiver) acoustic sensors that are commonly referred to as echo sounders. Operating between 20-30 kHz, a cylindrical array transducer was used to detect killer whales in Norway (source level 211-218 dB re 1 μ Pa) [9.4] and bowhead whales in the Canadian Beaufort Sea (source level 215 dB re 1 μ Pa) [9.5]. An analysis of that system from the Beaufort Sea demonstrates some of the complexities associated with the background environment: with a downward refracting sound speed profile, average bowhead detection ranges were less than 1000 m, but when a near-surface (upper 30 m) acoustic duct was present, the detection range extended to 5000 m [9.5]. These detection ranges (in absence of the duct) are similar to those found by Lucifredi and Stein [9.6], who used a bottom-mounted cylindrical receive array to detect gray whales off the coast of California, with an estimated maximum detection range of 1000 m. Cylindrical arrays have also been used at higher frequencies between 110-120 kHz to track near-surface humpback whales [9.7] and were reported to reliably detect killer whales at ranges up to 400 m [9.4]. Other higher frequency systems have used planar receive arrays, including the experimental work by Miller and Potter [9.8] who used a truncated cylindrical projector and a planar receiver array operating at 86 kHz to detect both humpback whales and NARWs. This experimental system reported whale detections at ranges of 30-84 m, although a maximum achievable range was not specified. Similar systems are available commercially and report much larger detection ranges (e.g., several hundred meters [9.9], [9.10]). In one reported instance, a split-beam echo sounder was used to detect killer whales with a system operating at 200 kHz [9.11]. Other types of active acoustic systems may be worth considering for the purpose of detecting whales and/or reducing vessel strike risk but have not been reported on.

NARW Detection: TRL 4

Active acoustic sensors have been shown to detect whales in a limited set of environments. The relationship between environmental complexities and detection range remains a challenge, which must be addressed to improve detection reliability. Few studies have investigated NARWs specifically [9.8], and additional experimentation must be conducted in a wide variety of environments relevant to NARWs. To determine when and where active acoustic systems could be effective at detecting NARWs, these experiments should be conducted under a wide range of ambient noise and sound speed profile conditions, as well as spanning the range of water depths where NARWs are found.

Individual Vessel Risk Reduction: TRL 3

Active acoustic sensing has been discussed for the specific objective of onboard vessel strike reduction, but formal evaluations have not been conducted, and concerns have been raised regarding whale detection ranges and the time required for vessel evasive action [9.12]. Analysis should be completed to determine what type of vessels, and under what type of operating conditions (e.g., ambient noise, water depth, bottom properties, vessel speeds), active acoustic sensing could be used to reduce the risk of vessel strike.

Regional Risk Reduction: Not applicable

References:

- [9.1] R. J. Urick, *Principles of Underwater Sound*, McGraw-Hill, 1967.
- [9.2] X. Lurton, *An Introduction to Underwater Acoustics: Principles and Applications*, Chichester, UK: Praxis Publishing Ltd, 2002.
- [9.3] H. Medwin and C. S. Clay, *Fundamentals of Acoustical Oceanography*, San Diego, CA: Academic Press, 1998.
- [9.4] F. R. Knudsen, O. B. Gammelsaeter, P. H. Kvaldsheim, and L. Nottestad, "Evaluation of fisheries sonar for whale detection in relation to seismic survey operations," *Bioacoustics*, vol. 17, no. 1–3, pp. 326–328, Jan. 2008, doi: <https://doi.org/10.1080/09524622.2008.9753864>.
- [9.5] M. Geoffroy, S. Rousseau, and C. Pyc, "2011 Beaufort Sea Active Acoustics Survey for Marine Mammal and Pelagic Fish Detection," Technical Report, 2012.
- [9.6] I. Lucifredi and P. J. Stein, "Gray whale target strength measurements and the analysis of the backscattered response," *The Journal of the Acoustical Society of America*, vol. 121, no. 3, pp. 1383–1391, Mar. 2007, doi: <https://doi.org/10.1121/1.2436643>.
- [9.7] M. Bernasconi, R. Patel, L. Nøttestad, G. Pedersen, and A. S. Brierley, "The effect of depth on the target strength of a humpback whale (*Megaptera novaeangliae*)," *The Journal of the Acoustical Society of America*, vol. 134, no. 6, pp. 4316–4322, Dec. 2013, doi: <https://doi.org/10.1121/1.4826178>.
- [9.8] J. H. Miller and D. C. Potter, "Active high frequency phased-array sonar for whale shipstrike avoidance: target strength measurements," in *MTS/IEEE Oceans 2001*, 2001. doi: <https://doi.org/10.1109/oceans.2001.968324>.
- [9.9] G. West and N. Swift, "Enhancing ship safety with the navigation and obstacle avoidance sonar," in *MTS/IEEE Oceans 2017*, Anchorage, 2017. 7-35.
- [9.10] W. R. Glenn and C. M. Zimmerman, "Vector data extraction from forward-looking sonar imagery for hydrographic survey and hazard to navigation detection," in *MTS/IEEE Oceans 2015*, Washington, 2015. doi: <https://doi.org/10.23919/oceans.2015.7401889>.
- [9.11] J. Xu, Z. D. Deng, T. J. Carlson, and B. Moore, "Target Strength of Southern Resident Killer Whales (*Orcinus orca*): Measurement and Modeling," *Marine Technology Society Journal*, vol. 46, no. 2, pp. 74–84, Mar. 2012, doi: <https://doi.org/10.4031/mts.j.46.2.2>.
- [9.12] G. K. Silber, S. Bettridge, and D. Cottingham, Report of a Workshop to Identify and Assess Technologies to Reduce Ship Strikes of Large Whales, NOAA, 2008.

10 LIDAR

LIDAR, or light detection and ranging, is a remote sensing method that emits laser pulses that are then scattered from targets, allowing for range estimation and imaging over a wide field of view [10.1]. NOAA, for example, uses LIDAR, combined with sonar data, to create navigational charts [10.2]. LIDAR has been leveraged for a variety of fisheries applications, notably for the study of fish distribution, abundance, and behavior [10.3]. Additionally, research has been done on the use of LIDAR for marine animal detection and classification. Underwater LIDAR systems have been successfully shown to detect and classify artificial fish in a laboratory test tank, however environmental factors like strong currents and surrounding structures limit detection capabilities in an ocean environment [10.4]. Currently, there is no peer-reviewed literature regarding the use of LIDAR for whale detection, but these systems have been leveraged for marine mammal research. For example, the use of UAS mounted LIDAR for the measurement of whales and other large marine mammals has been tested [10.5]; in this use-case, small UAS flights were conducted to take images of whales at the surface after they had already been located.

NARW Detection: TRL 2

While the detection capabilities of LIDAR have been demonstrated for fish and other marine animals, no whale studies have been conducted. Additional research and experimentation, specifically on whales, is needed to further the potential of this technology for NARW detection.

Individual Vessel Risk Reduction: TRL 2

A proof-of-concept system has not yet been successfully established for LIDAR detection of NARWs from vessels.

Regional Risk Reduction: TRL 2

A proof-of-concept system has not yet been successfully established for LIDAR detection of NARWs at regional scales.

References:

- [10.1] U. Wandinger, "Introduction to lidar," in *Lidar*, New York, NY, Springer, 2005, pp. 1-18.
- [10.2] "BlueTopo: A curated collection of high resolution seafloor models," NOAA Office of Coast Survey. <https://nauticalcharts.noaa.gov/data/bluetopo.html> (accessed June 27, 2025).
- [10.3] J. H. Churnside, "Review of profiling oceanographic lidar," *Optical Engineering*, vol. 53, no. 5, p. 051405, Dec. 2013, doi: <https://doi.org/10.1117/1.oe.53.5.051405>.
- [10.4] F. Dalgleish *et al.*, "Undersea LiDAR imager for unobtrusive and eye safe marine wildlife detection and classification," in *OCEANS 2017 - Aberdeen*, Jun. 2017, doi: <https://doi.org/10.1109/oceanse.2017.8085029>.
- [10.5] S. M. Dawson, M. H. Bowman, E. Leunissen, and P. Sirguey, "Inexpensive Aerial Photogrammetry for Studies of Whales and Large Marine Animals," *Frontiers in Marine Science*, vol. 4, Nov. 2017, doi: <https://doi.org/10.3389/fmars.2017.00366>.

11 Tagging

Bio-logging and telemetry tags, hereafter referred to as ‘tags’, are physical monitoring devices used to provide a variety of environmental, physical, positional, and/or behavioral data from the animal to which they are attached. The data from these tags can either be stored onboard for later recovery (archival) or transmitted in near-real-time via electromagnetic or acoustic signals. A comprehensive discussion of the history of tag development can be found in [11.1], [11.2], [11.3]. Most near-real-time tagged-whale positional tracking has been performed using ARGOS satellites [11.4], while archival whale tracking is typically performed via an onboard inertial measurement unit (IMU) [11.5]. ARGOS tags advertise positional accuracies as high as 250 m [11.6] but are typically worse in practice when attached to whales. Alternatively, Fastloc GPS, an adaptation of traditional GPS that captures a ‘snapshot’ of the GPS satellite constellation in less than 1 s, improves accuracies to less than 30 m [11.7], [11.8]. It should be noted that when deployed, satellite tags can suffer from inconsistent updates, sometimes only a few times a day.

Non-invasive tags are commonly attached to whales, including NARWs, using suction cups that are deployed using hand poles or UAVs [11.1], [11.2], [11.9], [11.10]. Suction cup tags have been leveraged as research tools, providing audio, video, and position data at high rates. However, their useful attachment duration is short, remaining on the whales for hours to days and making them unrealistic for vessel strike mitigation. Therefore, they are not considered as part of this evaluation. Next generation non-invasive tags, such as those that leverage new adhesion technology, may provide a path forward for longer duration deployment; adhesion technologies are beyond the scope of this report.

This assessment considers anchored tags (Type A), bolt-on tags (Type B), and consolidated tags (Type C), each of which have been shown to be able to track whales for long periods of times (weeks to months). Type B tags are attached to the dorsal fin of an animal [11.11]; since the NARW does not have a dorsal fin, Type B tags are not considered here. Historically, both Type A and Type C tags have been used to study NARWs [11.12], but their use has been limited in recent years due to health concerns. Next generation Type C tags that penetrate the muscle/blubber fascia are under active development, and new designs have made significant improvements on prior shortcomings. State-of-the-art Type C tags are composed of a single solid body, created either through welded joints or via 3D printing [11.13], [11.14]. Recent Type C fascia-penetrating tags have shown average whale-tracking durations of 211 days in Southern Right Whales, with some lasting over 600 days. Shallower penetrating Type C tags, that extend only into the blubber layer, have been shown to last 23 days on average. These studies found minimal behavioral impacts and no long-term adverse health outcomes or evidence of infection from transdermal tags [11.14]. Less invasive than Type C, Type A tags leverage retention barbs that anchor to blubber beneath the skin layer. However, these tags are more likely to break off due to animal-to-animal contact; one study noted that Type A tag attachment lasted from 2 hours up to 50 days on NARWs [11.12]. There are several active permits for NARW Type A tag use in both the U.S. and Canada, which assume certain conditions are met (e.g., health assessment, not used on certain individuals including calves) [11.12].

NARW Detection: TRL 7

For tagging, TRL is evaluated based on the performance of the tag after deployment, meaning it is assumed that a tag can be safely attached to a NARW. Although suction-cup tags are commercially available and used routinely, they only provide positional information for hours to days and are therefore not considered as a detection technology in this context. Both Type A and

Type C tags, which have been used on NARWs, have the potential to provide positional data over a sufficient timescale to be used for detection purposes, providing whale locations for weeks or months after the initial attachment of the tag. Next generation Type C tags, which provide the longest duration of positional information, have been successfully demonstrated on Southern Right Whales [11.14] but have not yet been deployed on NARWs. Work remains to be done to design and demonstrate a long-duration tag that could be successfully approved for permitted attachment to a NARW. This could include development of novel non-invasive attachment mechanisms, or a comprehensive evaluation of the potential negative health impacts of next generation Type C tags on NARWs.

Individual Vessel Risk Reduction: Not applicable

Regional Risk Reduction: TRL 3

Tagging information is not currently used to inform dynamic management actions in either the U.S. or Canada. While a small number of Type A tags have been used in recent years to study NARWs in both countries, additional work must be done to establish how near-real time tagging data will be implemented into management processes. Questions remain regarding the necessary number of deployments (e.g., number of tagged animals, types of tags) to provide sufficient information to make a meaningful impact on vessel strike risk reduction. Challenges in deployment at scale (e.g., finding animals, making successful deployments) must also be addressed.

References:

- [11.1] R. D. Andrews *et al.*, “Best practice guidelines for cetacean tagging,” *IWC Journal of Cetacean Research and Management*, vol. 20, no. 1, pp. 27–66, Jan. 2019, doi: <https://doi.org/10.47536/jcrm.v20i1.237>.
- [11.2] D. W. Weller, "History of Tagging North Atlantic Right Whales: Gradualism and Punctuated Equilibria in the Evolution of Attaching Tags to Whales," in *North Atlantic Right Whale Tagging Workshop*, Herndon, VA, 2023.
- [11.3] B. Mate, R. Mesecar, and B. Lagerquist, “The evolution of satellite-monitored radio tags for large whales: One laboratory’s experience,” *Deep Sea Research Part II: Topical Studies in Oceanography*, vol. 54, no. 3–4, pp. 224–247, Feb. 2007, doi: <https://doi.org/10.1016/j.dsr2.2006.11.021>.
- [11.4] B. A. Block *et al.*, “Tracking apex marine predator movements in a dynamic ocean,” *Nature*, vol. 475, no. 7354, pp. 86–90, Jun. 2011, doi: <https://doi.org/10.1038/nature10082>.
- [11.5] M. P. Johnson and P. L. Tyack, “A digital acoustic recording tag for measuring the response of wild marine mammals to sound,” *IEEE Journal of Oceanic Engineering*, vol. 28, no. 1, pp. 3–12, Jan. 2003, doi: <https://doi.org/10.1109/joe.2002.808212>.
- [11.6] “SPOT Transmitting Tags,” Wildlife Computers Inc. <https://wildlifecomputers.com/our-tags/spot-argos-satellite-tags/spot/> (accessed Nov. 25, 2024).
- [11.7] L. M. Irvine, M. H. Winsor, T. M. Follett, B. R. Mate, and D. M. Palacios, “An at-sea assessment of Argos location accuracy for three species of large whales, and the effect of deep-diving behavior on location error,” *Animal Biotelemetry*, vol. 8, no. 1, Jun. 2020, doi: <https://doi.org/10.1186/s40317-020-00207-x>.

- [11.8] “SPOT-F - Wildlife Computers Inc.,” Wildlife Computers Inc., Sep. 25, 2018. <https://wildlifecomputers.com/our-tags/spot-argos-satellite-tags/spot/spot-f/> (accessed Nov. 25, 2024).
- [11.9] D. N. Wiley *et al.*, “Deployment of biologging tags on free swimming large whales using uncrewed aerial systems,” *Royal Society Open Science*, vol. 10, no. 4, Apr. 2023, doi: <https://doi.org/10.1098/rsos.221376>.
- [11.10] S. Parks and A. Shorter, "Suction cup high-resolution tags for cetaceans," in *North Atlantic Right Whale Tagging Workshop*, Herndon, VA, 2023.
- [11.11] R. D. Andrews *et al.*, “Best practice guidelines for cetacean tagging,” *Journal of Cetacean Research and Management*, vol. 20, pp. 27-66, Jan. 2019, doi: <https://doi.org/10.47536/jcrm.v20i1.237>
- [11.12] "North Atlantic Right Whale Tagging Workshop Report," Marine Mammal Commission, Feb. 2024.
- [11.13] A. Zerbini, D. Palacios, L. Irvine, A. Kennedy and F. Sucunza, "Type C or Consolidated Tags," in *North Atlantic Right Whale Tagging Workshop*, Herndon, VA, 2023.
- [11.14] A. N. Zerbini, J. Robbins, F. M. Gulland, N. Gales, M. Double and P. J. Clapham, "Assessing the Performance and Effects of Newly Designed Integrated Implantable Large Whale Satellite Tags. Final Report presented to the Office of Naval Research. Grant number: N00014-18-1-2749.," 2023.

12 Environmental DNA (eDNA)

Environmental DNA (eDNA) is DNA that is produced by an organism, in the form of shed body cells or waste, that is then collected from the environment. Among the uses of eDNA is the detection and identification of single species, using methods such as polymerase chain reaction (PCR) techniques to analyze the DNA samples [12.1]. The process of detection begins with the collection of a water sample collection. Samples are then processed to capture DNA, which is then analyzed to identify a specific species. If it is determined that a specific species DNA is present, it can be confirmed as a detection, indicating that the species was recently in the area where sample collection occurred [12.2].

eDNA has been proposed as a non-invasive method for marine mammal detection, and several studies have utilized the technique to detect whale species, such as [12.2], [12.3], [12.4], [12.5], [12.6], [12.7]. While experimentally proven, there are practical challenges associated with the use of eDNA, including understanding the rate of eDNA degradation as well as the fate and transport of eDNA as it is mixed and advected within the ocean environment. For example, Baker et al. [12.3] assessed the use of eDNA for detecting killer whales for up to two hours after their passage in waters that had been tidally advected by several km, although there were considerable variations in detection time and detection level and not all encounters produced detectable levels. Additional studies have also noted variability in eDNA detections over time after the surfacing of bowhead whales [12.6] or sightings of humpback whales [12.2]. Furthermore, current eDNA analysis techniques are costly and time consuming. This is, however, an active area of research that is developing rapidly. These developments include low-cost and automated methods for sample collection [12.7], [12.8] and new technologies aimed at improving eDNA assessment [12.1].

NARW Detection: TRL 3

eDNA has been shown to detect whales, but concerns exist regarding the variable detection levels. Many baseline research questions still need to be answered, including evaluating the persistence of eDNA particles, the required levels for detection, and the rate of degradation. Additional experimentation is required to answer these questions, including analysis of a more robust sample set for specifically NARWs.

Individual Vessel Risk Reduction: Not applicable

Regional Risk Reduction: TRL 2

While eDNA has been used to detect whales, experiments show that current methods are limited by fast degradation time and challenges with sample collection and analysis. For regional risk reduction purposes, there needs to be an accepted interpretation of eDNA detection in terms of whale presence at various spatial and temporal scales. Further, improvements in the sensitivity of PCR techniques, as well as developments to lower the time and cost of sample analysis, are required for this technology to be more effectively leveraged.

References:

[12.1] S. Ramírez-Amaro, M. Bassitta, A. Picornell, C. Ramon, and B. Terrasa, “Environmental DNA: State-of-the-art of its application for fisheries assessment in marine environments,” *Frontiers in Marine Science*, vol. 9, Dec. 2022, doi: <https://doi.org/10.3389/fmars.2022.1004674>.

- [12.2] S. E. Alter, C. D. King, E. Chou, S. C. Chin, M. Rekdahl, and H. C. Rosenbaum, “Using Environmental DNA to Detect Whales and Dolphins in the New York Bight,” *Frontiers in Conservation Science*, vol. 3, Feb. 2022, doi: <https://doi.org/10.3389/fcosc.2022.820377>.
- [12.3] C. S. Baker, D. Steel, S. Nieu Kirk, and H. Klinck, “Environmental DNA (eDNA) From the Wake of the Whales: Droplet Digital PCR for Detection and Species Identification,” *Frontiers in Marine Science*, vol. 5, Apr. 2018, doi: <https://doi.org/10.3389/fmars.2018.00133>.
- [12.4] C. V. Robinson, K. Dracott, R. D. Glover, A. Warner, and A. Migneault, “DNA from dives: Species detection of humpback whales (*Megaptera novaeangliae*) from flukeprint eDNA,” *Environmental DNA*, vol. 6, no. 2, Mar. 2024, doi: <https://doi.org/10.1002/edn3.524>.
- [12.5] G. Boldrocchi, L. Conte, P. Galli, R. Bettinetti, and E. Valsecchi, “Cuvier’s beaked whale (*Ziphius cavirostris*) detection through surface-sourced eDNA: A promising approach for monitoring deep-diving cetaceans,” *Ecological Indicators*, vol. 161, p. 111966, Apr. 2024, doi: <https://doi.org/10.1016/j.ecolind.2024.111966>.
- [12.6] D. Szekely *et al.*, “Environmental DNA captures the genetic diversity of bowhead whales (*Balaena mysticetus*) in West Greenland,” *Environmental DNA*, vol. 3, no. 1, Jan. 2021, doi: <https://doi.org/10.1002/edn3.176>
- [12.7] E. Boyse *et al.*, “Environmental DNA reveals fine-scale spatial and temporal variation of marine mammals and their prey species in a Scottish marine protected area,” *Environmental DNA*, vol. 6, no. 4, July 2024, doi: <https://doi.org/10.1002/edn3.587>
- [12.8] N. Formel, I. C. Enochs, C. Sinigalliano, S. R. Anderson, and L. R. Thompson, “Subsurface automated samplers for eDNA (SASe) for biological monitoring and research,” *HardwareX*, vol. 10, p. e00239, Oct. 2021, doi: <https://doi.org/10.1016/j.ohx.2021.e00239>.
- [12.9] C. Preston *et al.*, “Autonomous eDNA collection using an uncrewed surface vessel over a 4200-km transect of the eastern Pacific Ocean,” *Environmental DNA*, vol. 6, no. 1, Aug. 2023, doi: <https://doi.org/10.1002/edn3.468>.

13 Dimethyl Sulfide (DMS)

Dimethyl Sulfide (DMS) is a chemical released by phytoplankton in response to zooplankton grazing [13.1]. This chemical has become an indicator of productive marine environments [13.2], where areas with high DMS concentration have high levels of prey. It has been proven that DMS gradients exist, creating the possibility that zooplankton predators leverage these paths to find these high prey areas [13.3]. Several studies have demonstrated that DMS may attract different species of marine life such as sea turtles [13.4] and seabirds [13.5], with recent investigations suggesting that baleen whales may have the ability to locate odorants like DMS [13.1]. Baleen whales have paired blowholes, and this pairing may allow them to determine the direction of their food source based on the smell of chemicals like DMS [13.1]. While no peer-reviewed studies focusing specifically on the NARW have been published, the morphology of its blowhole may indicate that it possesses this ability [13.6]. It should be noted that recent studies in Cape Cod Bay found that NARWs were seen in areas with high DMS concentrations, but formal results have not yet been published [13.6].

It has been proposed that tracking a whale's food source, instead of the actual whales, may provide a way forward for non-invasive tracking. There is potential to monitor chlorophyll, a proxy for phytoplankton, in real time, as high levels of chlorophyll are correlated to high levels of phytoplankton. NASA maintains a monthly map of these levels, leveraging a Moderate Resolution Imaging Spectroradiometer (MODIS) on their Aqua satellite [13.7].

NARW Detection: TRL 2

It is still a hypothesis that DMS could be used as an indicator for potential NARW foraging. Additional baseline research is required to provide empirical evidence to support these hypotheses, including specific experimentation focusing on the NARW.

Individual Vessel Risk Reduction: Not applicable

Regional Risk Reduction: TRL 2

Risk reduction cannot be achieved until the detection capabilities of DMS have been scientifically supported.

References:

[13.1] C. Ryan *et al.*, “Morphology of nares associated with stereo-olfaction in baleen whales,” *Biology Letters*, vol. 20, no. 1, Jan. 2024, doi: <https://doi.org/10.1098/rsbl.2023.0479>.

[13.2] B. Bouchard, J. Barnagaud, P. Verborgh, P. Gauffier, S. Campagna, and A. Célérier, “A field study of chemical senses in bottlenose dolphins and pilot whales,” *The Anatomical Record*, vol. 305, no. 3, pp. 668–679, Jul. 2021, doi: <https://doi.org/10.1002/ar.24703>.

[13.3] C. S. Endres and K. J. Lohmann, “Perception of dimethyl sulfide (DMS) by loggerhead sea turtles: a possible mechanism for locating high-productivity oceanic regions for foraging,” *Journal of Experimental Biology*, vol. 215, no. 20, pp. 3535–3538, Oct. 2012, doi: <https://doi.org/10.1242/jeb.073221>.

[13.4] G. A. Nevitt and F. Bonadonna, “Sensitivity to dimethyl sulphide suggests a mechanism for olfactory navigation by seabirds,” *Biology Letters*, vol. 1, no. 3, pp. 303–305, Jun. 2005, doi: <https://doi.org/10.1098/rsbl.2005.0350>.

[13.5] K. Owen *et al.*, “Natural dimethyl sulfide gradients would lead marine predators to higher prey biomass,” *Communications Biology*, vol. 4, no. 1, Feb. 2021, doi: <https://doi.org/10.1038/s42003-021-01668-3>.

[13.6] “Smelly Gas Helps Researchers Track Right Whales,” *sanctuaries.noaa.gov*. <https://sanctuaries.noaa.gov/news/mar24/smelly-gas-helps-track-right-whales.html>




[13.7] “Chlorophyll,” *earthobservatory.nasa.gov*, Feb. 29, 2020. https://earthobservatory.nasa.gov/global-maps/MY1DMM_CHLORA

Appendix A One-page TRL Primer



Technology Readiness Level

What is the maturity of a technology for a specific application?
What are the next steps for technology maturation?

	1	2	3	4	5	6	7	8	9
 Technology Maturation Steps	<p>Basic research, experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts, without any particular application or use in view.</p>	<p>Applied research, original investigation undertaken in order to acquire new knowledge. It is, however, directed primarily towards a specific, practical aim or objective</p>	<p>Proof-of-concept for system, process, product, service, or tool; this can be considered an early phase of experimental development; feasibility studies may be included</p>	<p>Successful evaluation of system, subsystem, process, product, service, or tool in a laboratory or other experimental environment; this can be considered an intermediate phase of development.</p>	<p>Successful evaluation of system, subsystem, process, product, service, or tool in relevant environment through testing and prototyping; this can be considered the final stage of development before demonstration begins.</p>	<p>Demonstration of a prototype system, subsystem, process, product, service, or tool in relevant or test environment (potential demonstrated).</p>	<p>Prototype system, process, product, service or tool demonstrated in an operational or other relevant environment (functionality demonstrated in near-real world environment; subsystem components fully integrated into system).</p>	<p>Finalized system, process, product, service or tool tested, and shown to operate or function as expected within user's environment; user training and documentation completed; operator or user approval given.</p>	<p>System, process, product, service or tool deployed and used routinely.</p>
 Example 1: Radar for Avoiding Collisions with Ships	<p>Heinrich Hertz experiments with radio wave reflections from metallic objects</p>	<p>Christian Huelsmayer applies Hertz's work to the detection of vessels and invents the Telemobiloscope.</p>	<p>Huelsmayer's approach is refined, ranging is added, and this first naval vessel is equipped with radar in Germany. Radar is not yet widely adopted.</p>	<p>Motivated by WWII, radar is rapidly advanced by several countries for military purposes. The term RADAR is coined.</p>		<p>Radar for collision avoidance is adopted by merchant mariners and is refined both in terms of technology and operating guidelines</p>		<p>Radar for detecting ships and avoiding collisions becomes an established tool that is widely available from several manufacturers</p>	
 Example 2: Radar for Avoiding Collisions with Whales	<p>To avoid collisions, whales first need to be detected. The feasibility of radar for detecting whales is evaluated in a limited set of environments, both shore- and vessel-based, and met with mixed success.</p>			<p>Where we are in 2025</p>					
<p>Key points: Technology Readiness Levels are application specific. In the examples described above, the same technology (radar) is evaluated for two different applications: avoiding collisions with ships and avoiding collisions with whales. The TRL's are very different for these two applications. Just being commercially available does not mean that a technology is at TRL 9 for all applications.</p> <p>It should be noted that there are often additional considerations that are part of a technology's successful use, and multiple technologies may need to be applied to most effectively tackle a complex problem like vessel strike risk reduction. For example, in the example of 'radar for avoiding collisions with ships', a mariner has to act based on the information available from the radar in order to successfully avoid a collision, and radar may need to be augmented with other devices such as foghorns.</p>									