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Detecting and Monitoring Marine Megafauna from Space: Exploring Opportunities in the Northeast Pacific

Report from webinar and workshop
November 2–3, 2022

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Ocean Decade Collaborative Center Northeast Pacific
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Contents

Territorial Acknowledgement

From the coast to the deep water and across boundaries and borders, we acknowledge the traditional, ancestral, and unceded territories of all the Indigenous peoples who have called the Northeast Pacific region home since time immemorial.

Suggested Citation

Tulloch, V., R. McPhie, J. Nelson, E. Rubidge, K. Sheps, R. Martone. 2023. Detecting and monitoring marine megafauna from space: Exploring opportunities in the Northeast Pacific. Ocean Decade Regional Collaborative Center for the Northeast Pacific and Canadian Department of Fisheries and Oceans, Victoria, BC, CA. 37 pages.

Acknowledgements

We thank all webinar and workshop participants for their contributions to this work. We thank, in particular, the presenters at the webinar and workshop, as well as those who reviewed and provided input to improve this report.

Webinar Presenters:

- Emily Charry Tissier, Whale Seeker
- Lianna Gendall, University of Victoria
- Ruth Joy, Simon Fraser University (SFU)
- Vienna Saccomanno, The Nature Conservancy (TNC)
- Julika Voss, BioConsult SH, SPACEWHALE
- Cortney Watt, DFO, Space Whales and Arctic Marine Mammals (SWAMM)
- Anne Webster, Hatfield Consultants, smartWhales stream 1

Northeast Pacific sunset by Romney McPhie

Executive Summary

Emerging technologies for detecting and monitoring large-bodied animals (also known as 'megafauna') are becoming increasingly important for assessing presence, abundance, density, distribution, and health status, and for mitigating threats to at-risk species. Recent work globally has shown that marine megafauna such as baleen whales can be successfully detected using very high-resolution (VHR) satellite imagery, allowing for scientific studies, monitoring, and forecasting in remote and inaccessible areas. Species such as southern right whales (*Eubalaena australis*) and North Pacific humpback whales (*Megaptera novaeangliae*) have been detected in commercial satellite images with resolutions finer than 50 cm.

In Canada, emerging technology projects have been in recent development. The Canadian Space Agency (CSA) in collaboration with the Department of Fisheries and Oceans Canada (DFO) and Transport Canada (TC) launched smartWhales in 2021, an initiative funding numerous research and development projects to leverage satellite detection data to protect the North Atlantic right whale (*Eubalaena glacialis*). In the Arctic, Whale Seeker and the Space Whales and Arctic Marine Mammals (SWAMM) program are using VHR satellite imagery to detect and estimate densities of medium-sized cetaceans—beluga whales (*Delphinapterus leucas*) and narwhals (*Monodon monoceros*).

To explore the potential applications of VHR satellite technology in the Northeast Pacific Ocean, DFO and the Ocean Decade Collaborative Center for the Northeast Pacific (DCC-NEP) co-hosted an online knowledge-sharing event on November 2 and 3, 2022, setting the stage for future collaborations to detect and monitor megafauna using space-based data and advanced analysis methods. This report details results from the event, with the aim of supporting ongoing, actionable dialogue across sectors and regions working to better understand and manage our ocean's megafauna. The specific objectives of the event were three-fold: (1) describe the current state of the science, including projects and programs underway nationally to internationally; (2) broadly discuss potential research opportunities and applications in the Northeast Pacific Ocean, including any benefits and barriers or obstacles; and (3) collectively lay out recommended next steps for implementation in the Northeast Pacific region.

Presentations spanned the breadth of past, current, and potential future use of VHR satellite imagery to detect marine megafauna. VHR satellite imagery was shown to be a powerful tool, especially in multi-modal monitoring systems, contributing data to find solutions for species conservation together with human use of the seas. VHR satellite imagery can be used alongside traditional survey

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methods to help fill knowledge gaps (e.g., in baseline studies, population assessments, environmental impact assessments), and thus help evidence-based decision making. It can be used to survey large areas, provide snapshots in time, inform presence/absence of species, determine distribution and density of individual species, and detect both adults and juveniles.

Key issues discussed with respect to the specific applicability of VHR satellite technology to detect marine megafauna in the Northeast Pacific included:

- Environmental conditions may impede detectability;
- Species differentiation remains a challenge, especially in species-rich areas;
- Imagery tasking and analysis are time-consuming and can be costly;
- 'Real-time' detection is still out of reach;
- There are large logistic and technical challenges associated with storage capacity of satellite imagery coupled with significant amounts of data; and,
- Availability bias needs to be accounted for.

Specific needs or gaps were identified to help move from idea to action, including the necessity of collaborative work, data and image sharing to help reduce user costs, developing high quality and accessible training datasets for automation, building expert human capacity (particularly for automated systems), enabling data storage and data sharing, improving the provision of satellite technology products, investing in long-term solutions to automation, and identifying priority areas for satellite tasking.

A continued and concerted exploration of the potential use of VHR satellite imagery in the Northeast Pacific region was recommended, to encourage the adoption of this novel technology when and where it will effectively supplement traditional surveys and to support applications looking to efficiently monitor species and promote their survival and recovery. This can be achieved by building a community of practice that would bring together interdisciplinary experts in satellite imagery, automation and artificial intelligence (AI), and marine megafauna identification. A decision tree was identified as a potentially useful method for evaluating the utility of different technologies, especially if paired with a cost-effectiveness analysis, to help users identify which methods are the most "data for your dollar".

Use of VHR satellites should be a component of a multi-modal solution, and should augment, not replace, other survey methods (e.g., boat- and/or aerial-based surveys). The technology, however, is advancing at a rapid rate and opportunities for its use are expanding. The findings from this event point to the interest in and usefulness of VHR satellite imagery for applications in the Northeast Pacific Ocean to detect, assess, and monitor marine megafauna across multiple spatial and temporal scales. Given the current pace of environmental changes around the world and the rapid technological advances underway, integration and collaboration across disciplines and between organizations of various types are the keys to unlock a future where VHR imagery can be an effective and efficient tool to help answer critical management questions for marine megafauna at the regional and global scale.

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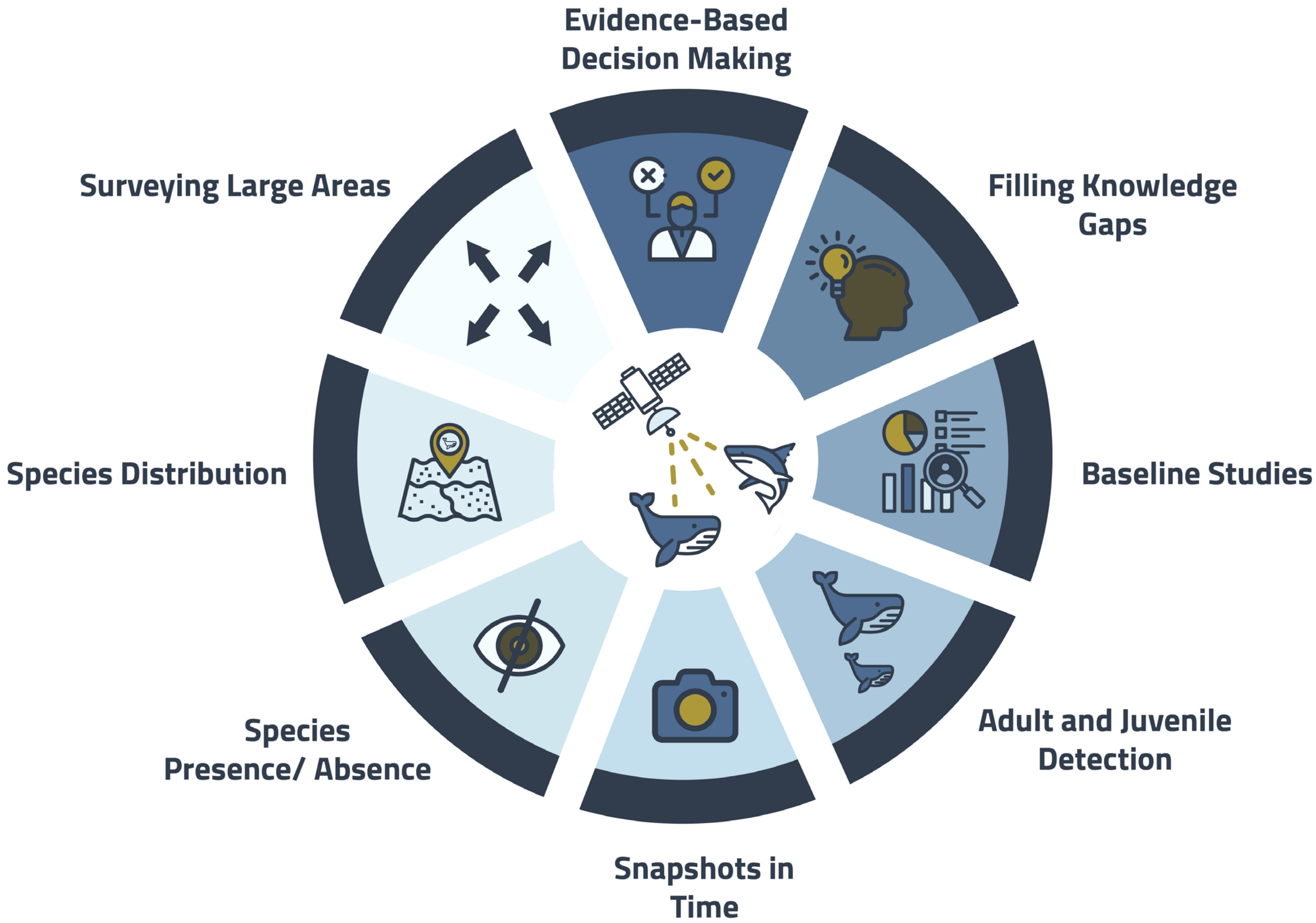


Figure 1.

VHR satellite imagery can be used for a variety of purposes to fill knowledge gaps related to large marine megafauna.

Acronyms

AI – Artificial Intelligence

API - Satellite Application Programming Interface

BAS – British Antarctic Survey

B Corp – B Corporation, a private certification of for-profit companies of social and environmental performance

CNN – Convolutional Neural Network

CSA – Canadian Space Agency

DFO – Canadian Department of Fisheries and Oceans/Fisheries and Oceans Canada

IOCCG – International Ocean-Colour Coordinating Group

MPA – Marine Protected Area

NEP – Northeast Pacific

NGO – Non-government organisation

NIR – Near infrared

NOAA – National Oceanic and Atmospheric Administration

PAM - Passive Acoustic Monitoring

QA/QC - Quality Assurance/Quality Control

SARA – Species at Risk Act

SARP – Species at Risk Program

SFU - Simon Fraser University

SRKW – Southern Resident Killer Whales

SWAMM – The Space Whales and Arctic Marine Mammals (Program)

TC - Transport Canada

TNC – The Nature Conservancy

UN – United Nations

UPC - Polytechnic University of Catalonia

VHR - Very high resolution (satellite)

Technical Terminology

Availability bias - Aerial and ship-based surveys count the portion of the population available at the surface and within the visible area of the water column, and through various measures account for the proportion that were not available to be detected by the observers. This ‘availability bias’ can be substantial and has a large impact on the abundance estimates if bias correction is not applied to the abundance estimate or if the correction is inaccurate.

Crowdsourcing - A process in which a large number of people (paid or unpaid, with varying levels of expertise) collect and/or process datasets.

Downsampling - The process of changing the spatial resolution of an image, by reducing the number of pixels in a given image.

Hyperspectral remote sensing - A technique that measures a wide spectrum of light, or samples a wide variety of bandwidths in the light spectrum, instead of just assigning primary colours to each pixel of an image. This technique aims to provide a rich dataset to detect objects of interest not visible to single-bandwidth imaging sensors.

Multispectral remote sensing - These sensors capture light in specific ranges of the electromagnetic spectrum, involving multiple typically broad bands, which can be viewed together to make a true or false colour image. Multispectral remote sensing enables analysts to differentiate objects that are hard to tell apart in the visible band.

Pansharpening - During pansharpening, the panchromatic band (which captures a wide range of the electromagnetic spectrum and creates a greyscale image) is combined with multispectral bands to enhance the resolution of a colour image to that of the resolution of the panchromatic band.

Hosting a Dialogue to Evaluate the Utility and Feasibility of Remote Sensing of Large Marine Megafauna in the Northeast Pacific Ocean

The Northeast Pacific Ocean is a large, highly productive region with increasingly variable oceanic conditions. Vast areas of remote ocean are punctuated by areas experiencing high levels of human activity. Marine megafauna species are wide-ranging and found at relatively low densities. Several megafauna species, such as the blue whale (*Balaenoptera musculus*), fin whale (*Balaenoptera physalus*), killer whale (*Orcinus orca*), and basking shark (*Cetorhinus maximus*), are listed under Canada's *Species at Risk Act* (SARA) as either endangered or threatened. Researchers and managers are working on understanding and conserving marine megafauna found in the Northeast Pacific Ocean. A key challenge for these ocean practitioners is how to effectively and efficiently detect, monitor, and protect megafauna, especially for species that have experienced historical declines in the region. Traditional surveys using boat, land, and aerial platforms, and utilizing methods such as visual observations and Passive Acoustic Monitoring (PAM) are continually increasing our understanding of at-risk marine megafauna and their habitats. A question has surfaced of how novel technologies, which could include environmental DNA (eDNA) to ocean gliders to very high-resolution (VHR) satellites, could be used alongside traditional survey methods to build understanding of and improve the way we manage our complex coastal ecosystems.

Figure 2.

The Northeast Pacific region includes the Northeast Pacific Ocean sub-basin and adjacent coastline of Canada, the USA and Mexico (Baja California to Alaska inclusive).

VHR satellite technology is rapidly-developing. Recent foundational work on VHR satellites has shown that whales and other large-bodied marine animals can be successfully detected from space. Animals as varied as African elephants (*Loxodonta Africana*) to polar bears (*Ursus maritmus*) to masked boobies (*Sula dactylatra*) are being successfully detected and monitored from space using this technology. Marine megafauna species are proving to be good candidates for VHR satellite detection because of their large bodies, the contrast many species exhibit against their ocean environments and the fact that many species congregate for feeding and breeding . In the Northeast Pacific Ocean, with its wide diversity of megafauna inhabiting coastal and offshore waters, this technology has yet to be put to use. An opportunity was identified to host a conversation to address the following questions: ***How can we use this technology in the Northeast Pacific? Can it be used to tackle a broad range of applications, from understanding marine species' populations, to marine protected area monitoring, and threat mitigation?***

To spearhead this conversation, an online knowledge-sharing event consisting of a public webinar (November 2, 2022) and an invitational workshop (November 3, 2022) was held to set the stage for future collaborations to detect, monitor, and forecast megafauna in the Northeast Pacific using space-based data and advanced analysis methods. This event was planned by a coordinating committee composed of representatives from the Department of Fisheries and Oceans Canada (DFO), the Tula Foundation's Ocean Decade Regional Collaborative Center for the Northeast Pacific (DCC-NEP), and The Quadra Centre for Dialogue. The event was designed to allow an international group of researchers, managers, and practitioners an opportunity to directly share experiences, successes, and challenges related to surveying whales using VHR satellite imagery. Participants (see Appendix A1) also showcased learnings and new initiatives that may contribute to improving projects and programs—those currently underway and those to be considered in the future.

For complete event agendas, see **Appendix A2.**

Goals of the Event:

1. To facilitate the transfer of knowledge and ideas related to the application of VHR satellites to the detection and monitoring of marine megafauna;
2. To explore opportunities for programs or projects in the Northeast Pacific Ocean that advance or utilize VHR satellite technology to detect, monitor, or forecast the distribution of marine megafauna;
3. To build relationships between research groups, ocean managers, and the public to:
    a. Encourage data and information sharing;
    b. Integrate activities where possible to improve efficiencies; and,
4. To inspire future formalized collaborations and partnerships for cost-sharing and/or leveraging funding, and ongoing knowledge-building.

The **specific objectives** of the event were three-fold:

1. Describe the current state of the science, including projects and programs underway internationally to nationally;
2. Broadly discuss potential research opportunities and applications in the Northeast Pacific Ocean, including any benefits and barriers or obstacles; and,
3. Collectively lay out recommended next steps for implementation in the Northeast Pacific region.

WEBINAR: Cross-Cutting Themes and Case Studies from the Webinar Presentations

The public webinar was designed to provide presentations from diverse expert groups on the research and applications of VHR satellite imagery for detecting and monitoring megafauna. Presentations focused on past, current, and potential future programs and projects. Presentations were delivered in two blocks, with a moderated discussion after each block and an open discussion to close the webinar (see **Appendix A3** for biographies of the presenters).

Where Do We Currently Use Remote Sensing To Detect And Monitor Marine Megafauna And What Have We Learned From Existing Programs And Projects?

Block 1 Presentations:

Julika Voss, BioConsult SH, SPACEWHALE

"SPACEWHALE: Surveying whales from space as an effective tool for baseline studies and respective monitoring"

Cortney Watt, DFO, Space Whales and Arctic Marine Mammals (SWAMM)

"Eye in the sky: Arctic whale abundance and estuary use from space"

Emily Charry Tissier, Whale Seeker

"Scaling satellite use for marine mammal detection - requirements and expectations"

Anne Webster, Hatfield Consultants, smartWhales stream 1

"smartWhales Space-Based Detection System: successes and challenges so far"

Cross-cutting themes across all presentations in Block 1 (see **Case Studies A–C**) included some of the **benefits** and **challenges/limitations** of using VHR satellite imagery to detect marine megafauna and considerations for future projects.

March 9, 2015 Right Whale #2790 and Calf, Aerial View by Georgia Wildlife Resources Division is licensed under CC BY-NC-SA 2.0.

Benefits discussed included:

VHR satellite imagery can be a powerful tool, especially in multimodal monitoring systems, contributing data to find solutions for species conservation together with human use of the sea;
VHR satellite imagery can be used to fill knowledge gaps (e.g. baseline studies, population assessments, environmental impact assessments), and thus help evidence based-decision making; and,
VHR satellite imagery can be used to: survey large areas, provide snapshots in time, inform presence/absence of species, determine distribution and density of individual species, and detect both adults and juveniles (e.g., see SPACEWHALE, Case Study A).

Challenges and limitations included:

VHR satellite imagery cannot deliver real-time, fine-scale resolution information compared to other methods such as drone imagery;
Tasking satellites is very expensive, and temporal and spatial mismatches between satellite imagery and the presence of whales are likely;
Analysis of VHR satellite imagery is very resource intensive, and cloud cover or detection difficulties can hinder accuracy;
There are limitations of this process in providing abundance estimates, in part due to high uncertainty in the depth constraints for whale detection in the water by satellite imagery; and,
There are several challenges surrounding ground-truthing VHR imagery.

Figure 3.
The benefits and challenges of using VHR satellite imagery to detect marine megafauna, as discussed by the webinar presenters.

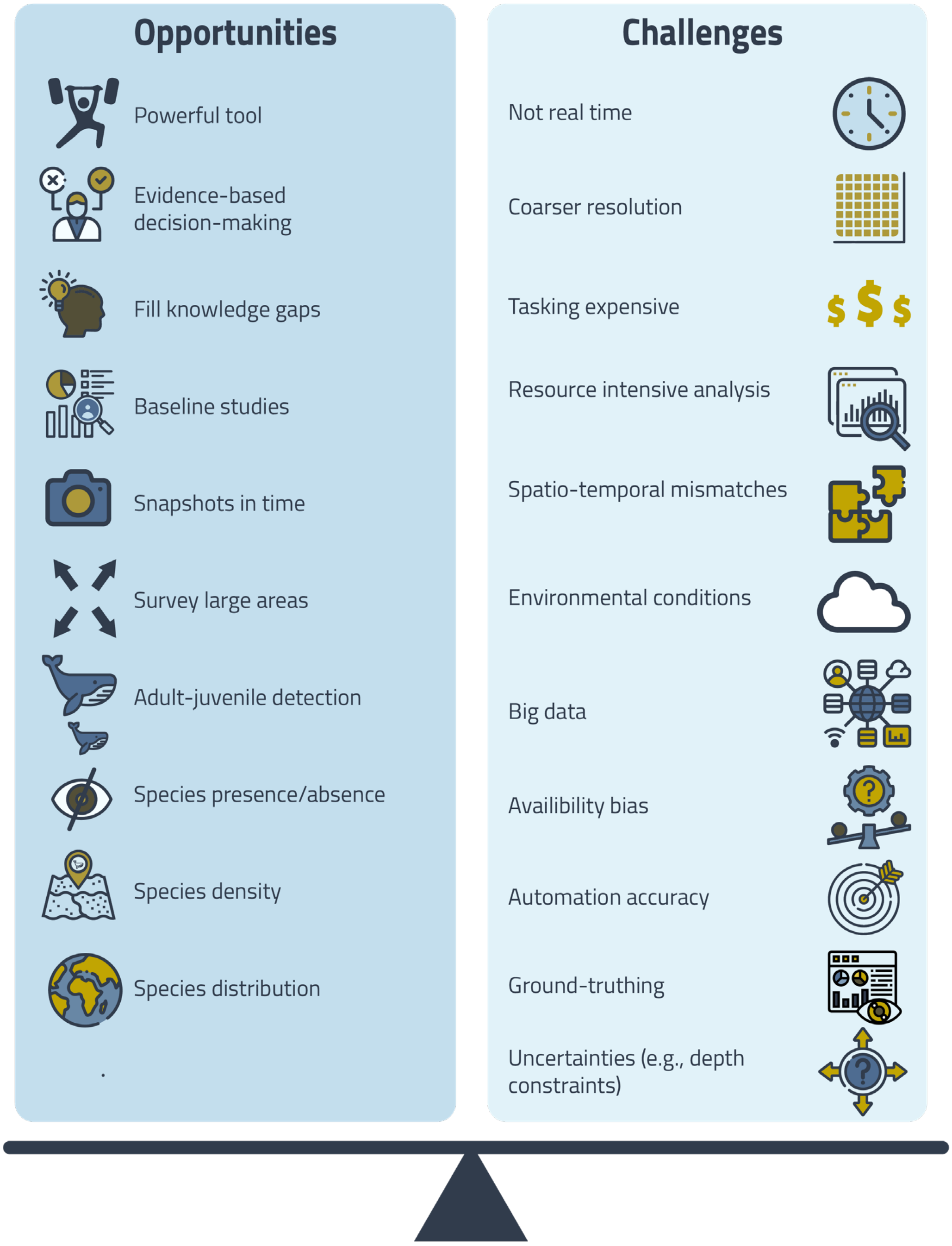


Figure 4.

Programs and projects using VHR satellite imagery to survey and manage marine megafauna need to balance the many opportunities (benefits) and recognized challenges (limitations).

All presenters agreed that VHR satellite imagery **should not and cannot replace all traditional methods** (e.g., boat- and/or aerial-based surveys) in every area, given its current limitations, but should instead supplement these methods. The technology, however, is advancing at a rapid rate and opportunities for its use are expanding. The finest resolution imagery that is currently commercially available is 30 cm, due to privacy issues and laws prohibiting the public distribution of lower resolution imagery. Technology exists for even finer resolution imagery (10 cm) and is forecast to become publicly available in 2024. Several satellite providers also offer an upsampling process from 30 cm resolution to 15 cm resolution; but, this comes at an added expense.

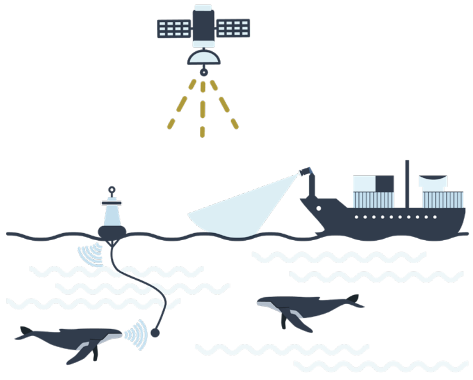


Figure 5.
VHR satellite imagery can supplement traditional survey methods such as boat-based surveys and acoustic methods (credit for original image: E. Charry Tissier)

Some misconceptions about the utility of satellite imagery for monitoring were discussed. These included the use of hyperspectral images and pansharpening methods (see technical terminology definitions) to try to improve whale detection in imagery, which may not be necessary or useful. Pansharpening and hyperspectral methods can produce superfluous data features, increasing data analysis resource requirements and costs, and may not help to answer the question(s) of concern. Several recommendations were made, including the need for users to be specific about their research question(s), and understand what data are needed to answer their question(s), before using pansharpening or other methods. Some experimentation has been conducted with multispectral imagery by smartWhales, using eight or four bands instead of three, but preliminary assessment shows limited added value. Further experimentation will be conducted by smartWhales at the coastal interface using multispectral imagery.

Solutions to the relatively **high cost of tasking satellites** were discussed, including the use of archived imagery which could be used as a cost-saving option if imagery exists for a particular area of concern. It is, however, difficult to acquire serendipitous or historical data for certain geographies, e.g., east-west spans or open ocean away from the coast. Ground-truthing can be done relatively cost-effectively by using drones and subsequently matching up images (but this is still limited by spatio-temporal mismatches in imagery)—see, for example, the SWAMM beluga whale project (**Case Study B**), and the SPACEWHALE program (**Case Study A**). Some cost comparisons between survey methods have been conducted by researchers at the British Antarctic Survey (BAS), suggesting that cost reductions for traditional methods typically come down to logistics and geographical considerations, versus VHR imagery for which costs are relatively standard around the world. Traditional aerial survey methods can be cost equivalent to VHR imagery if an aircraft is available and located in the region to be surveyed. However, the likelihood of an aircraft being available at the time and location of a survey is typically low; thus, satellite imagery and/or drone survey methods are often cheaper.

Surveying for whales by Romney McPhie

Case Study A: SPACEWHALE

SPACEWHALE is a service provided through BioConsult SH and HiDef Aerial Surveying Limited and applied around the world, across four continents so far, to detect whales. It combines artificial intelligence with quality assurance using an expert review team. Successful surveys have been conducted in Hawaii, the coast of Argentina, the Pelagos Sanctuary, the Bay of Biscay, Auckland Islands, and the Gulf of California. During these studies, whales were identified to species level and adults and juveniles were distinguishable.

SPACEWHALE has been used to detect Southern right whales in Port Ross, New Zealand, formerly a whaling ground. Southern right whales dramatically declined in the first half of the 19th century, with numbers increasing recently. Using archival imagery from WorldView-2 satellite, SPACEWHALE detected mother-calf pairs. Distribution maps were developed using this imagery, with different likelihood categories based on detection accuracy. Findings were compared with boat-based survey data and demonstrated that SPACEWHALE findings are comparable to results of traditional survey methods. In other study areas, SPACEWHALE detected whales which were, for example, flipper slapping or fluking, demonstrating that these behaviours can be seen in satellite imagery.

A Basking Shark by yohancha, is licensed under CC BY-ND 2.0

Case Study B: Belugas and SWAMM

In the Arctic, aerial surveys using human observers and camera footage have previously been used to monitor whale and other marine mammal populations. A recent project conducted by DFO Space Whales and Arctic Marine Mammals program (SWAMM) investigated the utility of also using satellite imagery to inform abundance estimates. Species at Risk Nature Legacy funding was provided to develop a program focused on the utility of using satellite imagery to monitor distribution and abundance of SARA listed species (two beluga populations) and the program was expanded to include narwhal, bowhead whale, (*Balaena mysticetus*) and walrus (*Odobenus rosmarus*).

The initial focus of the investigation was the Eastern High Arctic-Baffin Bay beluga whale population. The population is data deficient, with the last abundance estimate from 1996 estimating approximately 21,000 belugas. In August 2020, satellite images were used to evaluate the distribution and abundance of these beluga whales in estuaries where they are known to congregate in the High Arctic. SWAMM tasked WorldView-2 and -3 satellites through Maxar to get high resolution imagery due to the relatively small size of the cetaceans. The tasking resolution was 30-50 cm (30 cm preferably), with cloud cover <15%. Although expensive, this ensured the imagery would be specifically targeted to estuaries of concern. Although many estuaries were tasked, only a small sample of estuaries had imagery taken. Similarly, temporal mismatches occurred between satellite imagery and the presence of whales in estuaries. Due to the high number of images, crowdsourcing was used to count whales in tiles using a certainty scale. This process was good at eliminating large swaths of open water, but was biased towards false positives. Due to the limitations of satellite imagery processing, abundance estimates could not be immediately developed from the images. Instead, this process was able to provide density estimates, either relative to the other estuaries tasked in the project, or across time. This information could be useful to identify critical habitat or areas to be considered for protection.

The SWAMM program is also investigating haul out areas for walrus in the Arctic. The 30 cm resolution, however, is not fine enough to detect individual walruses. Because of this, outputs from satellite imagery are being supplemented with density estimates from traditional aerial methods to estimate abundance for this species.

Automated solutions have been proposed to address analysis bottlenecks, but there are a number of challenges and considerations to automating **and training** the analysis of VHR imagery. Fully automated solutions are in the process of being developed (e.g., smartWhale, **Case Study C**), versus semi-automated solutions that are already being used (e.g., the SWAMM program, **Case Study B**), but these are all proprietary at the moment and not publicly available.

Considerations related to **automation** and **training:**

- Training algorithms is data, labour, and time intensive;
- Fully-automated processes may require thousands of image examples for training purposes alone, especially if using hyperspectral images. Because of this, pipelines for image processing must be robust to dealing with big data; and,
- Labeling quality must be high to be useful for any applied purpose; and,
- Not only are a large number of training images required (**especially for fully-automated solutions**) but imagery also needs to span the distribution of expected appearances.

The SPACEWHALE algorithm was shared as an example of an automated process that was initially trained using photographs from digital aerial surveys from HiDef Aerial Surveying, downsampled to the resolution of satellite imagery. Subsequently, downsampled drone photographs from various scientists and species were used for algorithm training. Satellite imagery from previous SPACEWHALE projects is now being used to further train the algorithm.

Despite these challenges, presentations and discussions emphasized that shortcuts should not be taken during the training process.

Case Study C. smartWhales stream 1 space-based detection system Hatfield Consultants and partners

smartWhales (2021-2023) is an initiative funded by the Canadian Space Agency, with support from Transport Canada and Fisheries and Oceans Canada, aiming to develop space-based methods to monitor endangered whales and, in particular, the endangered North Atlantic right whale (NARW). Five companies and their collaborators were funded; out of these five consortiums, three are focused on the detection and monitoring of NARW using VHR imagery (stream 1) and two are focused on the prediction and modeling of NARW habitat (stream 2).

The consortium led by Hatfield Consultants is currently in year two of a three-year project, and has just completed their first demonstration of the detection system. The main objective of the stream 1 smartWhales project is to use satellite detection to support systematic and adaptive monitoring efforts for the NARW, using fully-automated artificial intelligence (AI) with cloud storage for wide-area monitoring. Their system includes an AI model retraining capability to enable continued improvements. An output Application Programming Interface (API) is being developed for user analysis and visualizations with other data sets.

Both archive and tasked Maxar imagery have been used to date on the project. In coordination with the other smartWhales stream 1 consortia, they tasked imagery over Cape Cod Bay during spring 2022 and the Gulf of St. Lawrence during summer 2022, based on historical whale aggregations locations during those times of the year. True colour (e.g., R,G,B) bands were used, pansharpened to either 30 or 50 cm, to help pre-train the model and detect subtle whale features. The detection process is fully-automated once image data are uploaded to the cloud storage, with pre-processing steps including image chipping and enhancement and rendering for better visibility of objects. Image chips are then processed by two AI models. The first model acts to pre-screen data containing mostly open water, and extracts only chips likely to contain objects of interest in them. Chips with an object of interest are then processed with the second model which provides a bounding box around any detected objects including whales.

The AI models used in the first demonstration were trained with a very small dataset, with only generic whale detection used due to difficulties in being able to detect different species based on the size of the training dataset. Human validators went through all chips via a custom labeling tool to confirm the results, with a subsequent quality assurance process

Another consideration for automated solutions is how to measure accuracy when ground-truthed data are not available. One solution proposed is to use expert human observer(s) to ensure a “gold standard” in accuracy, for example, a highly trained marine biologist that is experienced in satellite image detection. By treating the algorithm as one observer and comparing its outputs on images analyzed by an expert human observer, the “accuracy” of the automation can be measured by evaluating whether the inference falls in between the values from the observers. Similar processes of testing accuracy have been used by smartWhale, SPACEWHALE, and Whale Seeker. As described above in the context of the SPACEWHALE algorithm, there are also other sources of data for whales that can complement satellite imagery, such as aerial and drone data, that can be downsampled and used for training algorithms. Such methods were trialled in the smartWhales project (see **Case Study C**), but there were two key problems with these data. Firstly, once downsampled to 30 cm pixels, many images were too small for the input needed by the AI model. Secondly, the downsampled images looked too different from satellite data due to differences in camera sensors, objects, noise characteristics, etc. The solution to these challenges however, is part of a rapidly advancing field of research in AI, and there have been some new models advancing these techniques to ‘out-fill’ images and make them bigger, and to transfer the style of one image to another. The smartWhales project is planning a “hackathon” in the near future to get community help to solve this issue.

Other challenges concerning the use of automated AI models were discussed related to whale behaviour and the ocean environment. For example:

- Automation solutions can run into detection difficulties with groups of whales (especially if the groups are dense, as is sometimes the case in feeding or breeding aggregations), deep whales, or when whales are active at the surface (e.g., pectoral slaps) resulting in multi-segments; and,
- There is often a need to support various satellites to: (1) mitigate conflicts for a given orbit pass (other high priority users may task your satellite for a different area and/or purpose); (2) allow for a variety of local acquisition days and times; and, (3) to expand swath and area coverage. For example, the smartWhale project currently uses Maxar imagery but plans to expand to use additional sensors. The use of multiple sensors, although sometimes necessary, may result in the need for retraining, due to different sensor image properties.

Finally, users should consider ethics around how training sets are created, including how images are acquired and labelled, and what labour practices are employed (e.g., living wage payment, etc.). Policies should be in place governing development and use of AI tools (e.g., B Corp performance, accountability and transparency). Questions were raised concerning privacy laws around obtaining imagery of populated places or urban areas (particularly applicable for coastal regions); however, such imagery is rarely used as it increases land mass in images, which is cost ineffective.

Key Take-Aways

- Consider: Is VHR satellite the right technology to address the research or management question(s)?
- Consider the robustness of the image processing pipeline, and reduce superfluous data
- Ensure there is a measurable way to determine the quality and accuracy of detections
- Invest in long-term solutions to automation
- Use of VHR satellites should be a component of a multi-modal solution if possible, and should augment, not replace, other survey methods in areas that can be accessed (e.g., by boats).

Dec. 2013 Pregnant Right Whale Diving by Georgia Wildlife Resources Division is licensed under CC BY-NC-SA 2.0.

Work in Progress in the Northeast Pacific Ocean and Potential Applications

Block 2 Presentations:

Vienna Saccomanno, The Nature Conservancy (TNC)

"Advancing the detectability of humpback and gray whales in satellite imagery off California"

Ruth Joy, Simon Fraser University (SFU)

"Novel data inputs for forecasting movement of whales in the Salish Sea"

Orcas by Romney McPhie

Presenters discussed the potential use of VHR imagery to manage and mitigate threats to marine megafauna in the Northeast Pacific, and an open discussion exploring a range of potential applications in the Northeast Pacific concluded the webinar. Presentations introduced a feasibility assessment currently being undertaken on the development of automated species-specific detection approaches using VHR imagery focused on humpback whales and grey whales (*Eschrichtius robustus*) (see **Case Study D**), and the development of a real-time forecasting system for movement of Southern Resident Killer Whales (SRKW; *Orcinus orca*) near coastal shipping lanes in the Salish Sea (see **Case Study E**).

Entanglement in fishing gear is a leading cause of mortality in whales worldwide. The California commercial Dungeness crab (*Metacarcinus magister*) fishery has developed an early warning program to monitor and proactively mitigate entanglement risk to whales that requires frequent surveys of whales across fishing grounds; however, these surveys can be cost intensive and subject to logistical disruptions. The Nature Conservancy (TNC) and partners have been investigating VHR satellite imagery as a complement to traditional survey methods to survey whales along the coast of California (**Case Study D**). The overarching goal of this project is to develop a nimble tool that can provide timely information on the presence and distribution of whales to inform conservation decision-making.

Another threat facing whales worldwide is ship strikes. To help address this threat in the Salish Sea, researchers at Simon Fraser University (SFU), along with partners, have built a real-time forecast system to track movement of endangered SRKW in and near coastal shipping lanes (**Case Study E**). One of the key challenges in using satellite imagery is its inability to provide "real-time" monitoring due to temporal and spatial mismatches and delays or lags in the sensor tasking process. Their ultimate goal is to develop a multi-species real-time classification and forecasting system using AI and citizen science visual detections, through collaboration with various interest groups in the Salish Sea.

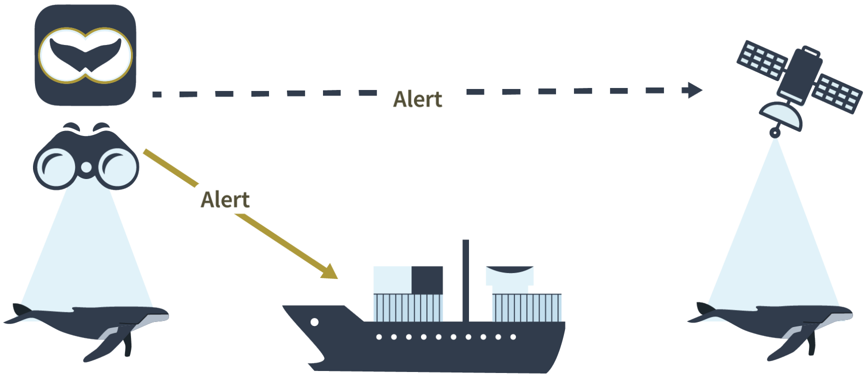
Case Study D: Automated species-specific identification on the California Coast using VHR imagery

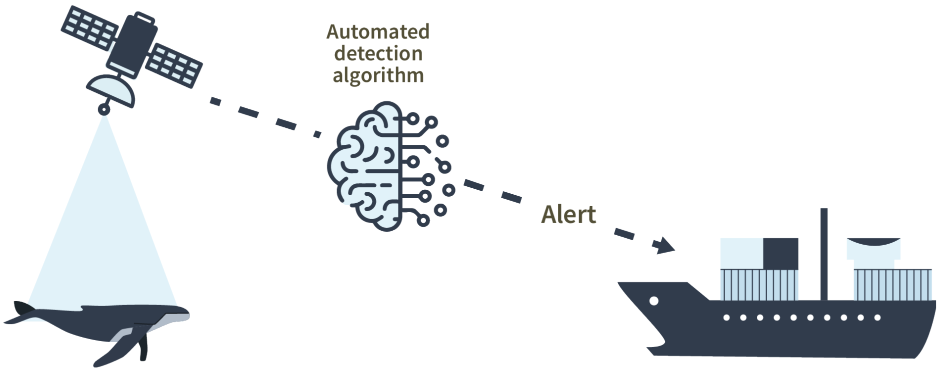
TNC and The Polytechnic University of Catalonia (UPC), in collaboration with marine mammal researchers with the National Oceanic and Atmospheric Administration (NOAA), is conducting a first order feasibility study developing and testing an automated framework for using VHR imagery along the California coast to monitor different species of whales, particularly humpback and grey whales. VHR satellite imagery (Maxar WorldView 3, and Airbus Pleaides Neo) were supplemented with aerial and unoccupied aerial vehicle (UAV) data for training. The technical approach to the modeling has been focused on building a modular framework using deep learning, computer vision, and statistical signal processing to develop high performance and species-specific algorithms. The project workflow is cloud based. Statistical analyses have been completed on humpback and grey whale data. Preliminary results using archival data are promising, with deep learning workflows able to detect grey whales even in unfavourable conditions. Continued stress-testing in more challenging and variable conditions where there is turbidity, unclear water, and rough sea states, as well as overlapping human activities, will be a component of the project. Automated detection performance will be assessed for potential application in informing whale entanglement risk mitigation and other priority conservation science and decision-making needs off of California.

Case Study E: Managing shipping threats to Southern Resident Killer Whales

A monitoring framework has been developed at SFU that uses real-time data (citizen science detections) and archived (historic) whale density maps as inputs to a state space data assimilation model framework to predict an ensemble of SRKW locations at future time steps. The forecast of future whale trajectories are used to evaluate spatial risk of whales moving into shipping lanes. The model is dependent on real-time whale detection updates, without which the predicted whale density region becomes more uncertain with time. Without real-time observation to update whale locations, the forecast density is still reasonably accurate up to 2 hours which is sufficient time for a commercial vessel to slow down or change its path to reduce collision risk. The model may be extended to use other data sources, such as VHR imagery; however, one of the key challenges in using satellite imagery in such a system currently is its inability to provide “real-time” monitoring due to temporal and spatial mismatches and delays or lags in the sensor tasking process. One way in which VHR satellite imagery might be used in the near future in the system is to improve the habitat occupancy models (past movements, and past density and occupancy), by incorporating archived satellite imagery specifically.

Humpback by ashala Tylor, is licensed under CC BY-NC 2.0





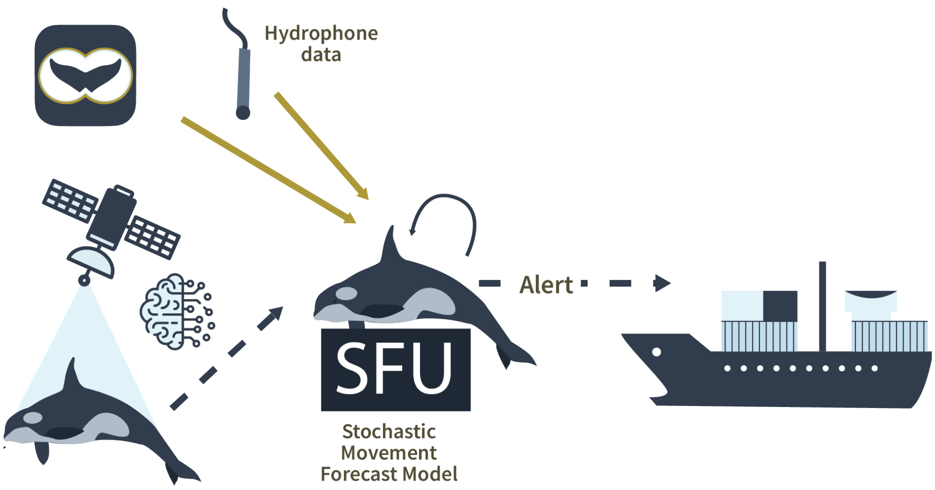


Figure 6.

Diagram of possible forecasting systems (with existing pathways in solid yellow and pathways in need of development in dashed blue) showing a tip and cue using the pre-established BC Cetacean Sighting Network (BCCSN) and the DFO Shark Sighting Network (SNN) (top image); (middle image) a satellite-based automated detection alert system; and, (bottom image) integrating a satellite-based automated detection system into a pre-existing forecast model for the southern resident killer whales developed at Simon Fraser University (SFU) by Dr. Ruth Joy and Dr. Marine Randon (Randon et al., 2022).

Potential Applications of VHR Satellite Imagery of Large Marine Megafauna in the Northeast Pacific Ocean

The potential applications of VHR satellite imagery in the Northeast Pacific Ocean related to marine megafauna are varied, ranging from building an understanding of marine species' populations, to marine protected area monitoring, to threat mitigation, to oil spill planning, preparedness, and response. During the final discussion, three key potential applications of VHR satellite imagery within the Northeast Pacific region were presented:

Orca by Wonderlane is licensed under CC BY 2.0

Species-At-Risk Recovery Planning and Implementation:

Romney McPhie, Science Coordinator, Hakai Institute and DCC-NEP; former Species at Risk Recovery Planner, DFO SARP

Within the 2020 SARA Action Plan for Basking Shark in Canadian Pacific waters, there are recovery measures that speak to investigating the use of emerging technologies and identifying potential collaborations to support a greater understanding of basking sharks in Canadian Pacific waters and beyond—could VHR imagery be used to help support basking shark recovery efforts in the Northeast Pacific Ocean?

San Diego Coast by Jim&Robin, is licensed under CC

Marine Protected Areas (MPAs) and Refuges In Canada:

Emily Rubidge, Research Scientist, Marine Spatial Planning, DFO Science

In Canadian Pacific waters, numerous marine spatial planning initiatives are underway, including the creation of a Northern Shelf Bioregion MPA Network protecting nearly one third of the bioregion (30,493 km^2). For MPAs to be effective spatial management tools, effective monitoring and enforcement frameworks need to be developed and implemented. There is the potential for VHR imagery to be used in MPA monitoring, for example both inside and outside existing MPAs to evaluate effectiveness, as well as in expanding MPA networks, for wide-ranging species including fin whales (*Balaenoptera physalus*), sei whales (*Balaenoptera borealis*), North Pacific right whale (*Eubalaena japonica*), humpback whales, basking sharks, grey whales, and killer whales. VHR imagery may be particularly useful for monitoring offshore MPAs such as SGaan Kinghlas – Bowie Seamount, where traditional monitoring is costly and logistically-complicated.

Humpback whale by FWC Research is licensed under CC BY-NC-ND 2.0.

Cetacean Population Monitoring:

Brianna Wright, Biologist, Cetacean Research Program, DFO Science

DFO's Cetacean Research Program (CRP) conducts population monitoring and ecological assessments for whale species, including at risk whales, using traditional platforms and methods (boat- and aerial- based surveys, PAM) and is interested in possibly supplementing traditional toolkits with satellite imagery methods for various applications, including in remote areas such as seamounts.

Key issues discussed with respect to the specific applicability of VHR satellite technology in the Northeast Pacific included the difficulty in distinguishing between species, and the need to account for availability bias. Potential collaborative efforts were raised, including a comprehensive Arctic observing network for freshwater, terrestrial, and ocean environments being proposed in the United States, and the potential use of VHR satellite technology to support this endeavour.

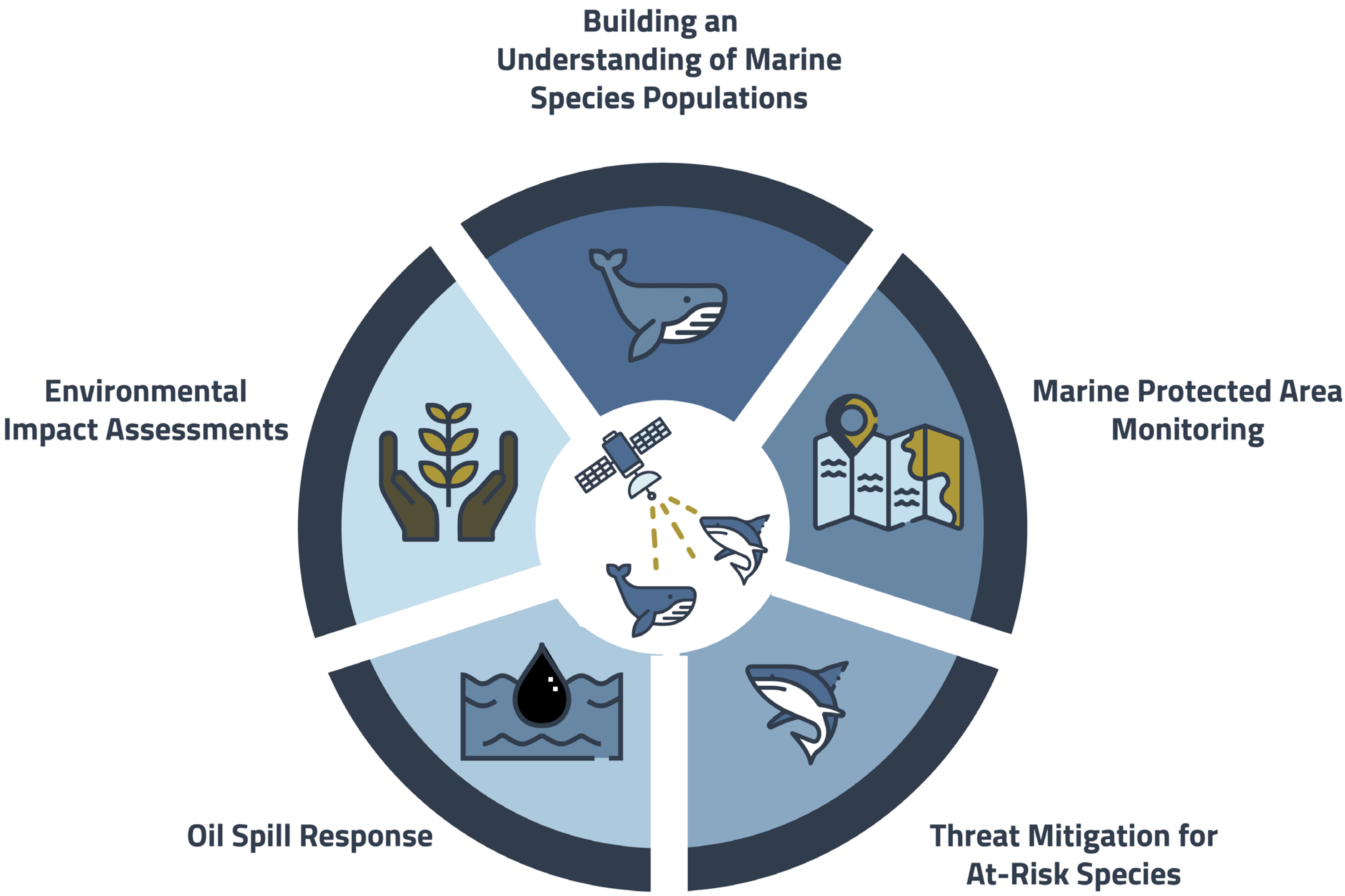


Figure 7.

Wheel illustrating some of the many potential applications of VHR satellite imagery in the context of marine megafauna .

WORKSHOP: Detecting and Monitoring Marine Megafauna from Space: Exploring Opportunities in the Northeast Pacific

The webinar was followed by an invitational workshop held online the following day, where participants (**see Appendix A1**) were invited to discuss topics of concern to the Northeast Pacific Ocean in question-based breakout sessions and a final wrap-up session. Two breakout sessions were held, with four groups in each session, during which the participants and facilitators used a Mural board to generate ideas and summarize key points for each question. The facilitators synthesized information across the breakout groups, in order to identify major themes, findings, and concerns.

The following is a summary of key points shared by participants in the workshop breakout groups for two topics: 1) Remote sensing, data accessibility and utility in the Northeast Pacific Ocean; and, 2) Co-design of VHR satellite monitoring with end users.

Remote Sensing Data Accessibility and Utility in the Northeast Pacific Ocean

What are some of the technical considerations related to remote sensing of marine megafauna in the Northeast Pacific?

Environmental conditions in the Northeast Pacific Ocean will likely impede detectability. Conditions that impede remote sensing methods include cloud cover, haze, fog, sea state, turbidity, ocean colour, ocean swell, waves, and wind. There is considerably more cloud cover in the Northeast Pacific compared to some other regions, and thus the amount of data needed to avoid clouds can be prohibitive if trying to cover large areas. Similarly, turbidity and sea state, which can affect availability bias, are major issues for coastal areas such as the Northeast Pacific. Solutions to addressing some of the environmental challenges include the development of algorithms to include wind speed to reduce bias from white caps, and combining weather models with imagery to help purchase imagery without cloud or swell to reduce costs.

Cloud cover and other environmental conditions such as ocean swell and waves in the NE Pacific region impede detectability of marine megafauna by NASA

Species differentiation remains a challenge, especially in species-rich areas. Discriminating between co-occurring species is challenging (for humans and algorithms), and higher resolution imagery in combination with improved algorithms are needed to decipher species. The behaviour of whales can affect detectability. For instance, humpback whale behaviour is more 'flashy' than that of grey whales (for example, humpback whales exhibit more breaching and tail slapping), so the footprint of a splash could be seen and used in addition to images of the whale itself to detect the presence of these more active whales. However, some species are too small for detection, let alone identification, using VHR imagery. Resolution and adjacency effects of VHR imagery are specific problems for fine detail and species identification. Additionally, in areas with high human activity, other objects such as boats and boat wake can hinder whale detection. Low data availability for AI is an issue, especially given species differentiation challenges; simulated data from aerial surveys, and from areas where a species is abundant (e.g., Ireland, for basking sharks), can help with algorithm training.

Imagery tasking and analysis are time-consuming and can be costly. The large size of the Northeast Pacific region may be a challenge for prioritizing locations to task satellites, and data requirements to overcome availability bias are huge, especially for large areas of interest or where there are low densities of species. Image procurement should be done 'tactically'; for example, tasking should focus on high-density areas such as feeding areas to reduce image areas with only water. Regardless of pre-planning, and as with other survey methods, mis-matches between species presence and satellite imagery are inevitable, and payment for tasked imagery is required regardless of the outcome (unless cloud coverage is >50% in the tasked images). Once imagery is tasked and purchased, many person hours are required to process and validate significant volumes of VHR imagery. Even in the case of automated detection (where systems are either semi- or fully-automated), there is a need for high quality training datasets. Crowdsourcing can be a very useful and cost-effective solution for building training datasets, especially in cases where binary detection (whale versus no whale) is needed, but likely needs to be confirmed by experts, for example, to ensure quality. Quality assurance and quality control (QA/QC) should be included as part of any crowdsourcing project. For federal agencies and others, securing and setting up finances to procure VHR imagery may be prohibitive until the technology is proven to be useful.

'Real-time' detection is still out of reach. The detection workflow, from satellite tasking to obtaining imagery to processing imagery to detecting objects and confirming detections, has time lags, meaning 'real-time' detection is still not possible using VHR satellite technology. The duration of the lag between tasking and obtaining imagery depends on the satellite (i.e., some researchers have experienced longer lags with Maxar compared to Airbus sensors). There are limited numbers of VHR imagery providers and tasking conflicts can occur with higher priority clients, as demand for certain times of the day can be high. There are also limitations when relying on only one satellite (due to likelihood of missing the target, or tasking conflicts). The extent of the area of concern can cause problems, with large east-west imaging being more difficult to capture at the same time than north-south extents. Because of these lags, use of tasked VHR imagery in real-time forecasting systems is not possible at this time.

Satellite in orbit by NASA

What are the opportunities/challenges/solutions related to data accessibility and data?

There are large logistic and technical challenges associated with the huge size of satellite imagery coupled with significant amounts of data. There is also a need for experts who can identify species in VHR imagery to aid in training and quality assurance. Shared data repositories or a central database are potential solutions for sourcing data (for example, training imagery), or sharing algorithms for automation. Such sharing would reduce person hours and increase efficiency; however, data and metadata management for shared repositories or databases would need to be carefully considered. End-user contracts with satellite providers might constrain the ability to share imagery, and costs may be higher for additional users when these contracts are in place.

Some specific opportunities or benefits related to data accessibility and sharing include:

- New satellites are continually being launched from countries worldwide (e.g., China, India), meaning more data sources are becoming available;
- There are companies, such as Skywatch, that have aggregated data sources which connect multiple commercial satellite imagery providers with organizations;
- Cloud services could be a good option for solving big data storage issues; and,
- Sharing data can be useful for public engagement, especially when studying megafauna (e.g., BAS is surveying albatross in the southern oceans partnered with NGOs).

Some potential solutions related to data accessibility and sharing include:

- Satellite data of the open ocean are currently underused, so some imagery might be free (or available at a reduced cost) from providers given a lack of competition for tasking or buying that imagery from other providers; and,
- Cost savings are possible via collaboration (e.g., academics are able to get imagery at a lower price).

What data/models exist to support tasking of VHR satellites in the Northeast Pacific Ocean for different uses?

Given the recognized limitations of the technology, VHR satellites should not be used in isolation but should form part of multi-modal approaches, complementing other traditional ocean science methods. In other words, VHR satellite imagery should be incorporated into integrated ocean observing systems. For example, PAM can be used to detect and obtain information on vocal species, such as killer whales, but other whale species are less vocal; satellite data might be the best way to obtain information on these relatively quiet species. Satellite imagery can also be particularly useful for obtaining data in remote areas where traditional methods are less feasible.

Supplementary and/or complementary data that could support VHR satellite monitoring and modelling efforts for whales in the Northeast Pacific Ocean include:

- historic whaling data,
- population surveys,
- historical and current observation data (e.g., sightings per unit effort from aerial and ship),
- distributional data,
- migration data,
- occurrence records,
- tagging and tracking data,
- acoustic data,
- predictive models,
- maps of prey or other proxies (e.g., plankton),
- primary productivity,
- local and Indigenous knowledge,
- habitat suitability models,
- climate and weather data,
- infrared data,
- ocean colour.

Some ideas for using satellite imagery as a complementary or substitute data source were suggested. For instance, sightings per unit effort can be used to define and understand habitat use, with a similar approach possible using satellite data. By weighting imagery data based on the density of whales in a given image, one can obtain a reasonable assessment of relative abundance in that image, as well as evaluate how relative abundance may vary over space and time.

Ocean colour and other environmental data are viable complimentary data for monitoring whales and whale mortality events. For instance, by correlating data such as harmful algal blooms (HABs), wind information and currents with archival imagery of historical strandings, it might be possible to predict where strandings might occur in the future.

One question raised was the possibility of identifying spectral signatures for different species, e.g., a potential unique spectral signature for sharks; however, space-based hyperspectral sensors do not currently have a high enough resolution to meet this need.


Ocean waves by Muffin Creatives sourced from Pexels

Co-Design Of VHR Satellite Monitoring With End Users

What considerations are needed for remote sensing data to be useful in different applications? How do requirements for end users (or groups of end users) of VHR data differ?

Probability of detection for a given location and species should be a key consideration. Size, contrast, and behaviour of target species, including seasonality, may differ considerably. Seasonality is a key factor when studying migratory megafauna. Projects focused on migratory species should be nimble or flexible enough to cover and change study areas according to seasonal sightings. It may also be better to target breeding grounds rather than foraging grounds for highly migratory species. Many species have different behaviours and movement patterns, and different signatures, affecting detectability.

The size of the species affects detectability, with finer resolution imagery needed than is currently available for some medium and smaller species. New satellites will be available in the next few years (10 cm resolution) that might be useful for other smaller-bodied species or darker species, although behaviour might be limiting. Despite the benefits of combining survey methods, the traditional method(s) chosen for combining with VHR satellite imagery have to be carefully selected depending on the species (e.g., acoustics data are ineffective for basking sharks, so tagging is an option).

In the context of cetacean strandings, most stranding reporting networks are biased toward populated coastlines. To address this bias, remote areas could be monitored over time using VHR imagery to identify locations where strandings happen frequently, to inform where investments and other resources are sent.

Species-specific identification in VHR satellite imagery is a challenge. Some management applications require species specificity (e.g., population recovery; versus threat mitigation). One option is to distinguish species based on group size (e.g., SRKW have distinctive group sizes in the Salish Sea versus other whales in the region that typically are alone or in smaller group sizes); however, this would require manual imagery analysis, as auto detector technology can have trouble with groups of whales. Methods typically used by defence organizations, such as using the wake behind vessels to detect vessels, could be applied to whales by using ripple patterns as a signature.

Availability bias is a major issue. Species-specific detection by VHR satellites at different depths, and depending on environmental conditions, remains a challenge, making abundance estimates using VHR satellites an area of research.

When tasking satellites, a number of considerations come into play. Tasking requirements and locations will differ depending on the project objectives (e.g., monitoring MPAs, versus analyzing population characteristics). Consensus should be reached during project design on priority areas where tasking will occur (especially in high demand locations/times), considering things such as cost, turnaround time for data availability, resolution issues, revisit frequency, and data storage. Timing needs for tasking imagery (e.g., low tide for kelp, calm seas for megafauna, etc.) will vary depending on the application. To address location feasibility for any project or program, mapping environmental information (e.g., cloud cover averages, wind speeds, sea state) could highlight the best areas to target with VHR satellites. Projects or programs requiring real-time data will need to consider the current delays in collection and provision of imagery. In addition, all projects/programs need to consider the amount and type of data needed for ground truthing and replicability of their processes.

When undertaking automation, there are specific considerations. These include:

- Applications that automatically enumerate targets should provide the confidence and error rates;
- There are significant personnel requirements (e.g., expertise needed for quality assurance and training), and projects/programs should anticipate personnel turnover when creating long-term solutions;
- There are AI needs for each type of application (animal detection versus detection of other objects); e.g., fully-automated methods will meet certain needs even if detection probability does not need to be 100%;
- AI algorithms should be made publicly available;
- AI technology for the Northeast Pacific Ocean will need to discriminate between multiple species; and,
- Management measures for marine mammals have high data standards and requirements (e.g., to close fisheries), with very limited tolerance for error, so automated detection methods still have to be validated manually.

Determining objectives and managing expectations are crucial. Before undertaking any project/program, overarching objectives should be agreed upon. Questions to ask when determining objectives might include:

- What management is needed, and what information is needed to inform this management?
- Is VHR imagery appropriate to meet the management needs/goals?

More specific questions might include:

- Does every individual need to be detected, or could fully automated methods (that may miss some individual animals) meet the management needs/goals?

An analysis of the cost of satellite data versus traditional methods (i.e., comparable cost-effectiveness) should be carried out prior to applying VHR satellite technology, and what the technology can deliver should be clearly articulated to any who may be using the data.

What needs or gaps can we identify to help move from idea to action?

Collaborative work is necessary and needed. Collaborative work could focus on building on data that are gathered for different purposes (for e.g., monitoring of fishing vessels) and correlating other datasets (e.g., weather, sea state, ocean colour). There are a number of large consortiums and groups worldwide working on complimentary projects that could be useful in terms of collaboration. Tapping into existing communities with remote sensing experts (e.g., the IOCCG International Remote Sensing group, Canadian Space Agency, NetCOLOR) to understand where there is existing data available, and what the technical considerations are related to these data, would be a good step. For example, ocean colour remote sensing has different resolutions so cannot be used to detect whales, but could be used to correlate where whales might be based on where zooplankton are concentrated. A community of practice that brings megafauna experts and remote sensing experts together on a regular basis would help address this need.

Data and image sharing can also help reduce user costs. End users often have different budgets (e.g., academics, NGOs, and government), and different timelines for projects. Some government agencies get VHR imagery for free; however, the high prices of satellite imagery make it difficult for other end users to obtain, such as NGOs, despite price reductions for these groups.

High quality and accessible training datasets are needed for automation. For automation, and especially species-specific detection, a key need is to build readily-available datasets (global to regional) for AI training covering a wide range of species and other objects. These could consist of both real data (from aerial, drone, and satellite imagery) and potentially artificial datasets (e.g., “cut and paste” fake whales into environmental conditions to train algorithms).

Expert human capacity is needed. Humans are still part of the equation, even in automated systems. Greater expert capacity, such as that required for automated system training and validation, is needed to meet growing demand. Regional capacity within the Northeast Pacific region is necessary, and could be built through investments in training opportunities for students and early career ocean professionals (ECOPs).

Data storage and data sharing are needed. GitHub could be used for sharing code, AI training datasets, and inventories of images with metadata. For imagery, specific sharing requirements need to be written into initial contracts with satellite imagery providers. Access to pre-existing detection algorithms/ semi-automated processing would ensure users are not 'starting from scratch' every time, reducing processing times.

Improvements in the provision of satellite technology are needed. Price reductions in satellite imagery would increase the use and utility of this technology for megafauna detection. Additional improvements to the technology would include a better pipeline for image acquisition, finer imagery resolution, the possibility to preview satellite imagery and/or conduct pre-assessment of sea state/ cloud cover (etc.) before imagery purchase, improved acquisition of east-west areas, and having a greater number of satellites to increase availability (while recognizing trade offs in space debris that comes from increased satellite deployment).

Protocols and increased communication are needed. Standardized detection protocol(s) to compare between users and years/areas would increase clarity and possibly uptake of the technology. Endorsement of crowdsourcing as a source of data validation could help with image processing. Greater reporting-out on the use of this technology for megafauna detection at established local conferences/ meetings (e.g., Salish Sea Symposium) could also increase clarity, uptake, and collaborations.

For the Northeast Pacific region, priority areas for satellite tasking need to be identified for each application. For threat mitigation, areas of high risk for large whales could be used as a starting point for tasking, based on risk modelling, even if these areas are not species-risk-specific. Alternatively, one could identify species that are high risk and in need of research and monitoring (e.g., Northern Resident Killer Whales (NRKW), basking sharks), and target critical habitat (e.g., rubbing beaches, in the case of NRKWs) or 'hot spots' (e.g., basking shark areas of high historical abundance or present-day sightings) for tasking. Other sources of data, for example aerial surveys which are mostly opportunistic currently on the Canadian Pacific coast, could be augmented to indicate where satellites could/should be tasked in the future. Once priority areas are identified by application, a crosswalk between applications could indicate where priority areas overlap, and hence where there may be VHR project or program efficiencies and synergies.


Humpbackwhale tail wave by Pascal is licensed under CC BY 2.0.

Key Observations and Next Steps

Some key needs emerged from the discussions over the two events pertaining to using VHR satellite imagery in the Northeast Pacific Ocean to monitor or manage whales, including:

- Trained capacity, i.e., the 'human-side' to algorithm development and image analysis to ensure quality assurance and quality control;
- Resources to purchase and analyze imagery, which may be prohibitive, especially across vast areas;
- Differentiation of whale species in VHR imagery to suit the Northeast Pacific;
- More reporting out on current projects, programs and initiatives, for example, at conferences and other meetings so that lessons learned are communicated broadly; and,
- A community of practice and open communication channels amongst those immersed in the field to facilitate collaboration and partnerships.

Although the technology is rapidly improving with advanced processing and automation techniques, a cautionary note was made to ensure traditional methods are not replaced by VHR imagery at this stage, but that they are supplemented and combined, especially as deep learning methods are developed, and as detection ability improves in both traditional and novel methods.

Finally, a recommendation was made for potential users to ask themselves, prior to project initiation:

- Is satellite imagery useful, or the right type of survey method, to meet my research or management objectives?

For instance, satellite technology may not be cost-effective for research and monitoring in the Salish Sea, where finer-scale monitoring for many species (e.g., killer whales) is underway using multiple methods, but it may be useful for monitoring open ocean areas, seamounts, and large, data-deficient whale species

Recommended Next Steps

Some broad solutions and recommendations were highlighted during the discussions, for application anywhere where VHR satellite imagery is already being used to study megafauna, and in areas where it is being considered. These included:

1. Developing data sharing solutions;
2. Sharing AI algorithms and techniques;
3. Developing open-source or shareable training imagery database(s);
4. Collaboration across groups and users;
5. Using crowdsourcing methods for imagery analysis and ground data where observers can be appropriately trained and there is sufficient QA/QC; and,
6. Using a multi-modal approach that incorporates other traditional survey methods if possible.

For application of this technology in the Northeast Pacific region (and beyond), a key recommendation was to build a community of practice with experts in satellite imagery, automation and AI, and marine megafauna. In a similar vein, a library of good training datasets of different Northeast Pacific species should be developed that could be used to train algorithms from all regions, not just the Northeast Pacific. A central database for training purposes would be helpful to test algorithms. Collaboration across aforementioned groups will be key to the success of these strategies.

Participants discussed the development of a structured decision-making process using a decision tree that might aid potential users of VHR imagery in the Northeast Pacific in deciding whether the technology is appropriate, and/or what other survey methods might be useful/complementary/more appropriate to the research question. The decision tree would involve a costing and utility framework, with a list of other considerations including the accuracy of each method, and applicability.

Questions to help guide the decision-maker might include:

- Is this an area that is challenging to access?
- Is this a species that is challenging to detect?
- Is the weather generally suitable for satellite imagery?
- What kind of spatial and temporal resolution do I need?

A cost-effectiveness analysis of the different methods might aid in determining the branches of the decision tree, or could supplement this idea, to help users identify which method is the most "data for your dollar".

One next step in the Northeast Pacific region could involve conducting a co-designed pilot project, or first-round feasibility study using a "plug and play" methodology (e.g., an already developed algorithm from another region).

Beluga Whale by Jason Pier in DC is licensed under CC BY-NC 2.0

Closing Thoughts

The findings from this workshop and webinar point to the interest in and usefulness of VHR satellite imagery for a number of applications in the Northeast Pacific Ocean to detect, assess, and monitor marine megafauna across multiple spatial and temporal scales. Good work in this field is taking place worldwide —including in other areas of Canada—but much more work is required given the current pace of change in environments around the world and the rapid technological advances underway. Integration and collaboration across disciplines and between organizations of various types are the keys to a future where VHR imagery can be an effective and efficient tool to help answer management questions for marine megafauna both at the regional and global scale.

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Appendices

A1. List of Participants

Convening Team		
Rebecca	Martone	Ocean Decade Collaborative Center for the Northeast Pacific
Kathryn	Sheps	Ocean Decade Collaborative Center for the Northeast Pacific
Romney	McPhie	Ocean Decade Collaborative Center for the Northeast Pacific
Jocelyn	Nelson	Fisheries and Oceans Canada
Emily	Rubidge	Fisheries and Oceans Canada
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Invited Participants		
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Amel	Ben Mahjoub	BioConsult SH
Charmaine	Bosse	Transport Canada
Andeol	Bourgouin	Universite de Laval
Cody	Carlyle	University of New Brunswick
Emily	Charry Tissier	Whale Seeker
Yasuni	Chiriboga	Shark Conservation, Costa Rica
Penny	Clarke	British Antarctic Survey
Adam	Comeau	Dalhousie University
Maycira	Costa	University of Victoria
Hannah	Cubaynes	British Antarctic Survey
Courtney	Edwards	CD Edwards Mapping
Peter	Fretwell	British Antarctic Survey
Mauvis	Gore	Heriot-Watt University, Marine Conservation International
Laurent	Giugni	Canadian Space Agency
Charles	Greene	Cornell University
Gin Swen	Ham	BioConsult SH
Matus	Hodul	University of Ottawa
Holly	Houliston	British Antarctic Survey

John	Iacozza	Fisheries and Oceans Canada
Thomas	Jaegler	Arctus
Ruth	Joy	Simon Fraser University
Mike	Kirby	Canadian Space Agency
Sean	MacConnachie	Fisheries and Oceans Canada
Diego	Madrigal	MSc student, Costa Rica
Kirsten	Mathison	Parks Canada
Cory	Matthews	Fisheries and Oceans Canada
Alexandra	McInturf	Oregon State University
Katherine	McKercher	Fisheries and Oceans Canada
Luba	Reshitnyk	Hakai Institute
Carrie	Robb	Fisheries and Oceans Canada
Emily	Rubidge	Fisheries and Oceans Canada
Joshua	Stewart	Oregon State University
Mike	Sylvester	Transport Canada
Scott	Toews	Fisheries and Oceans Canada
Olivier	Tsui	Hatfield Consultants
Vivitskaia	Tulloch	University of British Columbia
Juilka	Voß	BioConsult SH
Cortney	Watt	Fisheries and Oceans Canada
Anne	Webster	Hatfield Consultants
Brianna	Wright	Fisheries and Oceans Canada
Carmen	Wu	Dynamic Ocean Consulting Ltd
Harald	Yurk	Fisheries and Oceans Canada

A2. Daily Agendas

Day 1: Public Webinar

9:30 am	Welcome and Setting the Context
10:00 am	Presentation Block 1: Where do we currently use remote sensing to detect and monitor marine megafauna and what have we learned from existing projects?
10:40 am	Q&A and Moderated Discussion: VHR imagery access and governance
11:00 am	Presentation Block 2: Work in progress in the Northeast Pacific
11:20 am	Q&A and Moderated Discussion
11:40 am	Open Discussion: Exploring Potential Applications in the Northeast Pacific
12:15 pm	Closing Remarks
12:30 pm	Webinar End

Day 2: Invitational Workshop

9:30 am Welcome

- Shape of the day and community agreements
- Introductions

9:50 am Setting the Context

10:00 am Breakout Group: Remote sensing, data accessibility and utility in the Northeast Pacific.

- What are some of the technical considerations related to remote sensing of marine megafauna in the Northeast Pacific?
- Are there opportunities/challenges/solutions related to data accessibility and data sharing?
- What data/models exist to support tasking of VHR satellites in the Northeast Pacific for different uses.

10:50 am BREAK

11:00 am Breakout Group: Co-design of VHR satellite monitoring with end users

- What considerations are needed for remote sensing data to be useful in different applications?
- How do requirements for different end users (or groups of end users) of VHR data differ.
- What needs or gaps can we identify to help move from idea to action?

11:45 am Discussion: New ideas and next steps

12:30 pm Workshop Close

A3. Biographies for Presenters

Julika Voss, BioConsult SH, SPACEWHALE

Julika and collaborators from BioConsult SH and HiDef Aerial Surveying Limited have initiated the SPACEWHALE service, which counts whales from space using very high-resolution satellite imagery. These images are evaluated in a semi-automatic process combining state-of-the-art artificial intelligence and marine mammal experts' quality assurance. The SPACEWHALE service has already been applied in several projects globally: in the Mediterranean Sea, in the Bay of Biscay, off the Hawaiian Islands, off the Argentinian coasts, in New Zealand offshore waters and in the Sea of Cortez. Julika is a marine scientist at BioConsult SH and her research focus is on marine mammal ecology. She has gained practical experience in the Azores, Iceland, and Italy, as well as statistical experience in analyzing acoustic and visual data from marine mammals.

SPACEWHALE: spacewhales.de/

Cortney Watt, DFO—Space Whales and Arctic Marine Mammals

Dr. Cortney Watt is a research scientist with DFO in the Science Branch, Arctic and Aquatic Research Division, currently working on the Space Whales and Arctic Marine Mammals (SWAMM) program in the Canadian Arctic region. This program is focused on detecting and monitoring beluga whales, narwhals, bowhead whales, and walruses.

Emily Charry Tissier, Whale Seeker

Emily Charry Tissier is CEO of Whale Seeker, a Montreal-based startup that leverages AI to simplify whale monitoring. Whale Seeker is 'bridging the divide between profitability and sustainability by making whale detection fast, accurate, and accessible'. She is also a founder of the Whale Carbon Plus Project that is developing methodology based on remotely sensed images to quantify the contribution of whales to carbon sequestration and ecosystem resilience of the open ocean, and to compensate ocean stakeholders that actively protect them.

Whale Seeker: whaleseeker.com; Whale Carbon Plus: thewhalecarbonplusproject.com/

Anne Webster, Hatfield Consultants, smartWhales stream 1

Anne Webster is the project manager for the Hatfield Consultants smartWhales project. Hatfield oversees a consortium made up of collaborators from the University of New Brunswick, Duke University, AltaML, and the Canadian Wildlife Federation. Like the other consortiums in the Canadian Space Agency smartWhales program's stream 1, they are developing a system to automatically detect North Atlantic Right Whales from very high-resolution satellite imagery using deep learning and cloud computing.

Hatfield Consultants: hatfieldgroup.com

Vienna Saccomanno, The Nature Conservancy

Vienna Saccomanno is an Ocean Scientist with The Nature Conservancy California, where she focuses on making Earth Observation data actionable to inform strategic marine conservation efforts. Vienna and her colleagues at TNC California, The Polytechnic University of Catalonia (UPC), and NOAA have been leading a first-order feasibility assessment of using VHR satellite imagery to monitor humpback and grey whales off the coast of California to inform adaptive management of these important species.

The Nature Conservancy California: nature.org

Ruth Joy, Simon Fraser University

Dr. Ruth Joy is a professor in the School of Environmental Science at Simon Fraser University, where her lab focuses on computational and statistical tools to manage and minimize anthropogenic impacts on marine mammals and sea birds. Specifically, they are working on developing a real-time forecasting system for southern resident killer whales (SRKW) in the Salish Sea to minimize the occurrence of human/whale conflicts.

Dr. Joy: sfu.ca/~rjoy/

A4. Outstanding Questions Asked by Participants

Throughout the workshop and discussion, the facilitators compiled a list of outstanding questions asked by participants, which could perhaps be addressed in a follow-up workshop, or by a community of practice. These are listed below.

- What is the current minimum size that megafauna must be, to be detected by the highest resolution commercial satellites currently available?
- How might we use VHR (not biased by whale-watching, for example) to inform our habitat occupancy models?
- At what point might humans be 'removed' from the equation? In other words, is human involvement/ validation always a component, even in fully-automated systems? E.g., Once it is determined that an automated system falls within an acceptable level of inter-observer bias, is that system considered fully-automated and can it then detect whales on its own? Should there be some human quality assurance/quality control even with fully automated systems, so that continued training of the algorithm occurs?
- In theory, could an algorithm be created that is trained on numerous co-occurring species and objects—including things such as basking sharks, large whale species, kelp—and then tasked with the detection of a specific species/object, depending on the application?
- What is the processing speed of hardware required to run through a large spatial dataset to identify targets?
- Under ideal circumstances, and financial resources, what is the smallest target that can be detected?
- Can the infrared, or near infrared, band be used to identify targets that could be cetaceans?
- Can we apply the same algorithms in the Northeast Pacific that are being applied in other regions (e.g., smartWhales)?
- Is it possible for different satellites to correct for environmental conditions, in other words, address them at the hardware stage? (or do all these things need to be addressed at the post-processing stage?)Are different satellites already doing some of this? (Would be good to know when picking a satellite provider, along with response rate)
- What kind of capacity do we have, within the Northeast Pacific, to carry out pilot projects/ work using VHR satellites (currently and/or up-and-coming/early career scientists)? (determining capacity might be a next step!)
- With respect to training datasets, are all that are currently working in the field facing challenges with respect to using aerial and drone imagery to train their algorithms? Clarity needed: Can these datasets be used? If not (or even if they are usable), will there be enough imagery for the Northeast Pacific and the target species?