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A roadmap towards monitoring walruses from space

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Abstract

Walruses (*Odobenus rosmarus*) are experiencing rapid habitat change, concomitant with dramatic sea ice declines in the Arctic. Reduction in sea ice also creates the potential for reduced benthic production and heightened disturbance levels from increasing levels of shipping traffic in previously ice-covered areas. These stressors are creating a growing need to monitor how walrus populations are responding under the new conditions, through the production of accurate abundance estimates, population trend data, and updated distribution information. Most walrus stock assessments rely on counts of walruses at their terrestrial haul-out sites, which are spread across the Arctic, limiting the spatial and temporal extent at which they can be surveyed with current tools (boats, planes, and drones). Satellite imagery is an emerging monitoring tool that can sample anywhere on the Earth's surface and increase survey frequency. Herein, we lay a roadmap towards monitoring walruses from space by discussing: (1) walrus conservation needs; (2) satellite capabilities in relation to walrus monitoring; and (3) the current feasibility and future prospects of surveying walruses using space technologies. Satellite imagery has been used successfully to detect, and in some cases count walruses, highlighting its potential to be a complementary tool to traditional methods for monitoring walrus distribution. Validation studies and initial population assessments demonstrate the potential of this new approach.

Keywords earth observation, marine mammals, *Odobenus rosmarus*, pinniped, remote sensing, satellite imagery

Introduction

Walruses (*Odobenus rosmarus*) range across the circumpolar Arctic. They rely on sea ice for several aspects of their lives, including resting between foraging trips close to food sources and for giving birth. On-going declines in their sea ice habitat and other accelerating climate-related threats (e.g. increased shipping traffic in the Arctic, reduced prey availability) are projected to lead to population declines. Currently, walruses are classified as Vulnerable on the International Union for Conservation of Nature (IUCN) Red List (Kovacs 2025). Because sea ice is predicted to continue declining (Rantanen et al. 2022, Kim et al. 2023), it is crucial to enhance walrus monitoring to provide knowledge necessary for threat mitigation and conservation. Abundance and trends remain unknown across much of the walrus's range. However, conventional survey platforms (boats and aircrafts) are logistically limited in the geographical and temporal extent that they can cover, and costs limit the frequency at which surveys are conducted. Emerging platforms such as drones are being used increasingly (Boltunov et al. 2021, Fischbach et al. 2022) but this method also suffers from geographic and temporal limitations. Therefore, there is a need to investigate complementary alternatives, including use of Earth observation satellites (Boltunov et al. 2012, Zinglersen et al. 2020, Fischbach and Douglas 2021, Matthews et al. 2022, Sherbo et al. 2023, Cubaynes et al. 2024).

Satellites orbiting the Earth can collect imagery in places that have been challenging to monitor historically, and can increase survey frequency while being non-intrusive to the animals. Among the diversity of satellites collecting data about the Earth's surface, optical satellites are increasingly viewed as a complementary tool

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to monitor marine mammal occurrence and population parameters, such as distribution, density and abundance (LaRue et al. 2022, Khan et al. 2023, Lynch 2023, Attard et al. 2024). For walruses, there have been a number of recent pilot studies (Zinglersen et al. 2020, Fischbach and Douglas 2021, Matthews et al. 2022, Sherbo et al. 2023, Cubaynes et al. 2024, Fischbach et al. 2025) following earlier trials (Burn and Cody 2005, Boltunov et al. 2012) to assess the feasibility of using very high (<1 m) to medium (< 10 m) resolution optical satellite imagery to detect and count walruses from space. Synthetic aperture radar (SAR) satellites, which offer the advantage of seeing through clouds and darkness, are also being investigated as a tool to monitor walruses (Fischbach and Douglas 2021). Thermal infrared satellite sensors might also be an option, but this technology has not yet been explored due to the spatial resolution of sensors in operation, which is currently too low (100 m at best, Table 1).

As this new field of satellite population monitoring expands, there is a need to build strong foundations to ensure comparability between studies, through standardization, collaboration, and agreement on best practices. Here, we lay out a roadmap towards surveying walruses using satellite imagery by (1) establishing conservation needs, (2) outlining satellite capabilities, and (3) assessing the current feasibility, future prospects and recommendations to estimate walrus distribution shifts and population trends.

Walrus conservation challenges and needs

Climate change and the rapid decline of sea ice in the Arctic is predicted to impact several aspects of walruses' lives. They depend on sea ice to give birth and rest, and their main prey—bivalve molluscs—is also heavily dependent on fall-out from sympagic (sea-ice-associated) primary production (Fay 1982, Born et al. 1995, Grebmeier et al. 2006, Yurkowski et al. 2020, Keighley et al. 2021, Cautin et al. 2024, Niemi et al. 2024). Less summer sea ice over the continental shelf is resulting in Pacific walruses (*O. r. divergens*) shifting to land-based haul-out sites, where they may lose access to some prey fields, spend more energy travelling to feeding grounds, and be subjected to crowding and trampling-related mortality of young animals in the larger herds that are becoming more common (Kovacs et al. 2015, Udevitz et al. 2017). Less sea ice will likely intensify the exposure of walruses to killer whale predation and industrial disturbances, such as oil and gas extraction and shipping, the latter has already risen dramatically across the Arctic in the last decade (Kryukova et al. 2012, Aerts et al. 2013, Hauser et al. 2018, Keighley et al. 2021, PAME 2025). As a result, changes in walrus distribution and population size are expected and need to be monitored. Their sensitivity to climate-change-induced habitat loss is expected to cause population declines throughout most of their range, potentially more so for Pacific walruses than Atlantic walruses (*O. r. rosmarus;* Laidre et al. 2008, Lowry 2016, Kovacs et al. 2021). Modelled projections for Pacific walruses to 2100 support this assertion, predicting a worsening of the state of the subspecies and an increased susceptibility to stressors (Jay et al. 2011).

Conservation actions in place and recommended for walruses and their habitats include strengthening environmental regulation and oversight of industrialized activities with consideration of cumulative impacts, protection of important habitats including haul-out sites and feeding grounds, and international cooperation on managing populations shared across jurisdictions (Heide-Jørgensen et al. 2014, Wiig et al. 2014, Kovacs et al. 2015). In Canada, Greenland, Russia, and the United States of America, walruses are culturally, nutritionally, and economically important for many coastal Indigenous communities, and management of hunting at levels that can be sustained by walrus populations during rapid change and in the face of other stressors is also needed (Heide-Jørgensen et al. 2014, Wiig et al. 2014, Kovacs et al. 2015).

The basic population and habitat information needed to inform such conservation and management actions is currently incomplete (Kovacs et al. 2021). Of the 13 walrus populations across the Arctic (Fig. 1), aerial/ship-based surveys suggest that one is increasing and three are stable. The status of the remaining nine is unknown (Kovacs et al. 2021). Walrus habitat use is seasonally dynamic, and is currently changing due to rapid losses of their sea ice habitats (e.g. shifts by Pacific walruses to more land-based haul-out sites). In Svalbard, walruses are undergoing local expansion as they recover from heavy over-exploitation in the past (Kovacs et al. 2015). In addition to this dynamism, Arctic coastlines are vast and monitoring all potential and historic haul-out sites is logistically virtually impossible using conventional methods. Monitoring distribution shifts and obtaining population abundance and trends relies on walrus detection and enumeration via either the detailed delineation of walrus herds, and/or counting of individual walruses. Walrus surveys usually take place at terrestrial haul-out sites in summer, when sea ice concentration is at its lowest and walruses are most likely to haul-out on land. Surveying terrestrial aggregations avoids challenges of counting walruses on sea ice when they are widely dispersed, and allows for interannual comparisons because walruses tend to return to the same terrestrial haul-out sites each summer (e.g. Kovacs et al. 2014, Hammill et al. 2016, Kochnev 2019, Fischbach et al. 2022, Mikkelsen et al. 2024). However, in some cases, walrus stock assessment requires surveying across extensive ice-covered areas (Heide-Jørgensen et al. 2014). This demands synoptic satellite coverage of vast marine regions, combined with software capable of detecting walrus herds and ideally enumerating individual walruses. In addition to providing abundance estimates relevant for specific management purposes, such surveys also yield valuable insights into walrus habitat use and key foraging areas.

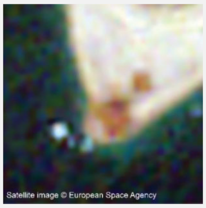
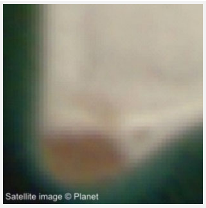
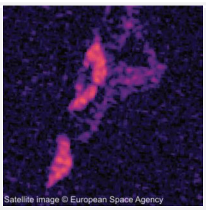
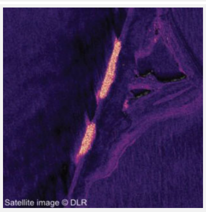
Filling knowledge gaps on distribution, population size and trends, and maintaining a reasonable currency of such information is a high priority for effective conservation of walruses (CAFF 2017). For assessing overall abundance trends and broad distribution shifts, monitoring intervals of five years are likely sufficient, but for populations under immediate threat or significantly depleted, shorter intervals (three years) may be needed. Satellite technologies offer great potential for augmenting traditional techniques to monitor walruses and their habitats.

Satellite capabilities

What satellites can see: types of sensors and spatial resolution

Earth observation satellites host different types of sensors, each collecting different information on features present on the Earth's surface (i.e. emitted electromagnetic radiation). Here, we focus on

Table 1 Overview of the different types of satellite sensors with potential applicability for walrus monitoring. A medium spatial resolution is between 100 and 10 m, a high spatial resolution is below 10 and 1 m, and a very high spatial resolution is below 1 m. Reference for satellite information: eoPortal 2024.

		Image examples	Satellites	Spatial resolution	Revisit rate*	Type of study	References
Optical sensors	Medium		Landsat constellation (8 & 9) Sentinel-2 constellation	15-30 m 10-60 m	8 days 5 days	Occurrence Seasonality Distribution Aggregation size	Boltunov *et al.*, 2021 Fischbach and Douglas, 2021 Fischbach *et al.*, 2025
Optical sensors	High		PlanetScope constellation Spot-6	3-5 m 1.50-2.50 m	1 day ≤ 5 days	Occurrence Seasonality Distribution Aggregation size	Fischbach *et al.*, 2025
Optical sensors	Very high		Eros-B GeoEye-1 Pléiades constellation Pléaides Neo constellation SkySat constellation WorldView-2 WorldView-3 WorldView Legion	0.70 m 0.41 m 0.50 m 0.30 m 0.50 m 0.46 m 0.31 m 0.30 m	2 days ≤ 3 days 1 day 2 times/day 12 times/day 1.1 time/day <1 day 15 times/day	Occurrence Distribution Aggregation size Count Density Abundance	Boltunov *et al.*, 2012 Zinglersen *et al.*, 2020 Fischbach and Douglas, 2021 Matthews *et al.*, 2022 Sherbo *et al.*, 2023 Cubaynes *et al.*, 2024
Synthetic aperture radar sensors	High to medium		RADARSAT constellation Sentinel-1 constellation	1-100 m 5-100 m	1-24 days 6 days	Occurrence Seasonality Distribution Aggregation size	Fischbach and Douglas, 2022 Fischbach *et al.*, 2025
Synthetic aperture radar sensors	High to very high		Capella constellation ICEYE constellation TerraSAR-X Umbra SAR constellation	0.25-1.20 m 0.25-15 m 0.25-40 m 0.25-1 m	4.8+ times/day <1 day 11 days 5+ times/day	Occurrence Distribution Aggregation size Count Abundance	Fischbach and Douglas, 2022 Fischbach *et al.*, 2025
Thermal sensors	Medium	No examples yet	Landsat-8 (TIR sensor)	100 m	8 days	Unknown	No studies yet
Thermal sensors	Very high	No examples yet	HOTSAT constellation**	3.5 m	10+ times/day (planned)	Unknown	No studies yet

*Revisit rate for the equator; it is shorter at higher latitudes, as these satellites travel on a sun-synchronous orbit (European Space Agency 2025).
** Constellation not in operation yet, due to satellite failure.

optical, synthetic aperture radar (SAR), and thermal infrared (TIR) sensors, because they are expected to be most useful to monitor walruses (Table 1).

Optical sensors passively collect information within the visible range of the electromagnetic spectrum (wavelengths between 380 and 700 nm), sometimes expanding to the near-infrared and short-wave infrared wavelengths (up to 2.5 µm; Dowman et al. 2012, Rees 2013). Most satellite-based walrus studies have used these types of sensors (Burn and Cody 2005, Boltunov et al. 2012, Zinglersen et al. 2020, Fischbach and Douglas 2021, Matthews et al. 2022, Sherbo et al. 2023, Cubaynes et al. 2024, Fischbach et al. 2025), because interpreting the output imagery is intuitive (and less ambiguous), as it looks similar to what the human eye normally sees, although this depends somewhat on the spatial resolution used (Table 1), as discussed below. Furthermore, being able to see the true colour provides additional details, essential in confirming that the observed features are walruses (e.g. a cinnamon brown area or scattered ellipsoids contrasting with their surroundings; Table 1, Fig. 2), which is not possible with SAR or TIR sensors. However, a major drawback of optical satellite imagery is that

Figure 1 Map of walrus distribution range adapted from Cubaynes et al. (2026), showing the different walrus populations and currently known haul-out sites for Pacific walruses (*O. rosmarus divergens*; Fischbach et al. 2016) shown as triangles and Atlantic walruses (*O. r. rosmarus*; Cubaynes et al. 2026) shown as points. The Baffin Bay population combines three populations and Hudson Bay–Davis Strait population combines three population too (Kovacs et al. 2021). The haul-out sites in the northern extant of the Southern Barents Sea population are classed as Atlantic walrus based on Semenova et al. 2019.

it cannot see through clouds, and it has potential problems with haze and low light levels.

SAR sensors actively measure the surface roughness and can be helpful to monitor walruses, particularly in cloudy situations and during the prolonged periods of darkness that extend throughout the Polar night in the Arctic, because these sensors are not light-dependent. They emit a radar pulse, a microwave signal (wavelengths between 1 mm and 1 m), at intervals that interacts with the Earth's surface. The intensity of the backscatter received from Earth is measured by the sensor and used to build images of the surface roughness, visualized as a brightness gradient (McCandless and Jackson 2004, NASA 2025). Walruses can be detected in SAR imagery (Table 1; Fischbach and Douglas 2021, 2022; Alaska Science Center 2022, Fischbach et al. 2025). So far, SAR has only been tested for sites where walruses haul-out on sandy beaches. Other haul-out substrates need investigation (e.g. rocky shores, beaches with boulders, etc.). Visually interpreting SAR outputs is not as intuitive as for optical imagery, and currently it requires validation with information on the ground, comparison with optical imagery, and/or multiple SAR images of the same location to per-

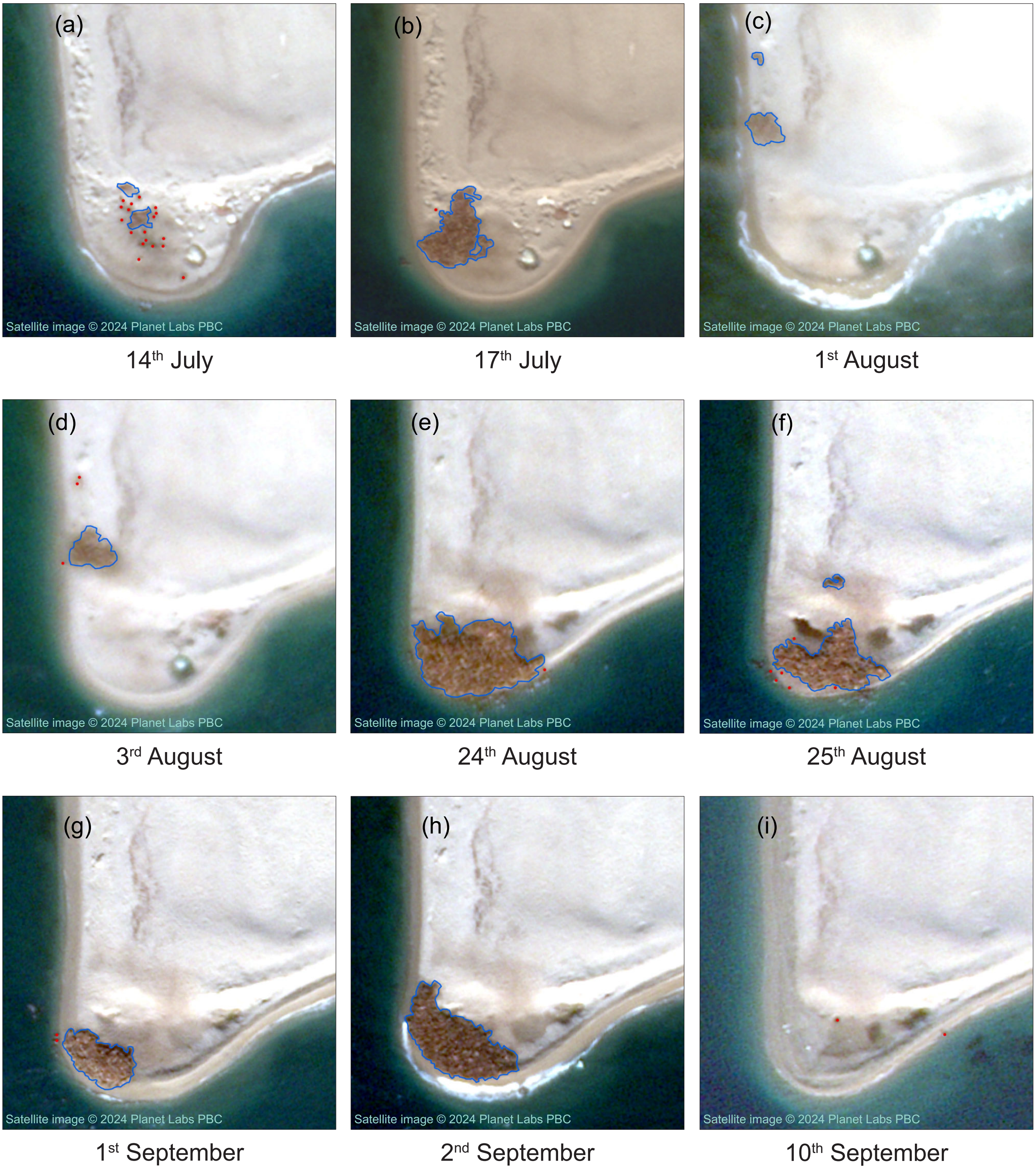


Figure 2 Timelapse of satellite imagery (PlanetScope satellite imagery, 3–5 m spatial resolution; satellite image © 2024 Planet Labs PBC) for the Torellneset walrus haul-out site in Svalbard, Norway, showing how dynamic a haul-out group can be**.** Tight herds of walruses are outlined in blue and visible individual walruses are labelled with a red dot.

form image differencing (e.g. walruses move while boulders generally do not).

TIR sensors passively measure the energy emitted from Earth, within the thermal infrared range of the electromagnetic spectrum (wavelengths between 2.5 and 12.5 μm). TIR imagery produces a heatmap of the Earth surface. It is expected that walrus herds could be visible as their heat signature is expected to be higher than their surroundings, although this remains to be tested.

All the sensors listed above provide information at different spatial resolutions, which will influence the level of detail visible and the sort of information that can be inferred from the imagery produced (Table 1). Here, we split spatial resolution into three categories: medium (500–10 m), high (<10 m to 1 m), and very high (<1 m) resolution. At very high spatial resolution (VHR), more details are visible, increasing confidence in the detection of animals, with potential to assess occurrence, count the number of walruses, or accurately outline tightly grouped walrus herd to estimate relative (e.g. area covered) or absolute (area covered x density) abundance (Boltunov et al. 2012, Zinglersen et al. 2020, Fischbach and Douglas 2021, Matthews et al. 2022, Sherbo et al. 2023, Cubaynes et al. 2024, Fischbach et al. 2025). For medium and high spatial resolutions, single animals will not be visible and assessing herd occurrences might be all that is feasible. Even then, small groups may be difficult to detect, with observations limited to groups of walruses above a certain number, likely above 100 animals (Boltunov et al. 2021, Fischbach and Douglas 2021). Estimating abundance with high or medium spatial resolution imagery may be feasible in instances where walruses are clumped in large groups (likely 1000 + walruses per group), so the area occupied can be measured (relative abundance estimate) and potentially used to estimate an absolute abundance if density estimates are available (either via a concurrent aerial or drone survey, or for well-studied haul-out sites previously recorded densities can be used to predict the density in the satellite imagery; Fischbach et al. 2025). However, the error associated with abundances estimated from high or medium spatial resolution imagery will almost certainly be higher than if using very high spatial resolution imagery.

Satellite imagery collection: access, temporal resolution and study location

Satellite imagery collection should be planned carefully, with consideration for whether the satellite of interest collects imagery continuously or requires tasking (i.e. requesting for imagery to be collected), accessibility (i.e. free or subject to payment), frequency and timing of imagery collection, and location of the study area, as this may limit the scope of a project. Medium spatial resolution satellites, such as Landsat-8 and 9, and Sentinel-1 and 2, continually collect imagery and are also accessible to users at no cost (ESA 2015, USGS 2024). Some high spatial resolution satellites, such as PlanetScope, take imagery continuously but may come at a cost if users are not affiliated with a university or an institution that has a contractual arrangement (Planet 2023, 2024). VHR satellites usually involve specific tasked image collection, which typically comes at a cost (Cubaynes et al. 2019, Attard et al. 2024). Costs may be lower for a project if it can make use of archival imagery rather than tasking new imagery, but accessibility is restricted to the VHR images that were previously collected and there are relatively few in existence currently for known walrus haul-out sites. A recent large-scale VHR optical satellite imagery collection effort (the Walrus from Space project) has contributed to available images for Atlantic walrus haul-out sites (for the 2020–2024 period; WWF-UK 2023). Additionally, speculative tasking (i.e. when a satellite operator proactively collects imagery over an area of interest with no specific purchase commitments) can also lower imagery costs, as this data can be purchased later when funds become available and at a lower cost once images reach archives. But acquiring imagery in this manner is suboptimal for monitoring programmes and planning projects.

The revisit rate of a satellite (or satellite constellation) defines the frequency at which a haul-out site can be monitored; typically revisit rates vary from multiple times per day up to a single monthly revisit depending on the satellite system (Table 1). Revisit rates of satellites currently in operation (Table 1) will not be limiting for surveys that require only one or a few images every several years, such as might be used to track broad distribution shifts. However, most other survey objectives require high frequency imaging of single sites (e.g. haul-out group dynamics, response to disturbance) or imaging of multiple sites within a relatively short period (e.g. stock or population abundance). For example, imagery collection with temporal gaps greater than a day or two may miss peak abundance occurrences, which would limit the utility of the monitoring data (Fischbach et al. 2025). In these instances, revisit rates can be restrictive and combining the use of different satellites with similar or different capabilities can improve the frequency at which haul-out sites can be monitored. For instance, collecting imagery from several VHR optical satellites can increase the temporal coverage and likelihood of acquiring a suitable image. This approach is being used by the "Walrus from Space" project (WWF-UK 2023). However, this approach comes at a financial cost, and it may be helpful to complement the collection of VHR data using freely available lower spatial resolution imagery, such as Sentinel-2 imagery. In addition to the sensor revisit rate, clouds limit the frequency at which a haul-out site can be imaged by an optical sensor. If cloud cover is a limiting factor in ensuring suitable temporal coverage, SAR imagery, which can see through clouds, can be a viable alternative for some studies, with medium spatial resolution available for free (e.g. Sentinel-1), and higher spatial resolution coming at a cost (e.g. TerraSAR-X). The frequency at which a given haul-out site can be imaged is expected to improve in the future as more satellites come into service, increasing the likelihood of acquiring cloud-free imagery.

Satellite image collection should be targeted for all known sites (Fig. 1) to achieve good global population coverage for walruses (and data should be synthesized and openly archived). Coverage could also be extended to search for new haul-out sites in areas used by walruses, although this is currently done opportunistically through manual imagery review and would benefit from automated systems improving systematic coverage. Known haul-out sites for Pacific walruses are generally well documented and publicly available (Fischbach et al. 2016, Fig. 1). Known haul-out sites for Atlantic walruses are not as complete and tend to be registered in different databases by country—Canada, Greenland and Norway (Born et al. 1995, Lydersen 2008, Higdon 2016, Hansen et al. 2018, Garde and Hansen 2021). Therefore, a publicly available dataset has been created collating all known Atlantic walrus haul-out sites in one location to facilitate access for satellite image-based applications (Cubaynes et al. 2026, Fig. 1).

Satellite imagery collection should take place in the summer or early autumn to coincide with maximum numbers of walruses being hauled out on land. Furthermore, summer is well suited to satellite imagery collection, particularly optical sensors, because the lack of sunlight in the Arctic from circa mid-October to mid-March (location dependant) prohibits monitoring. Satellite imagery collection must be timed to match regional terrestrial haul-out site usage over as short a period as possible to minimize likelihood of bias due to walrus movements among sites (weather permitting for optical imagery that gets obstructed by clouds). This will be impacted by the size of the area monitored, the revisit rate of the satellites used, and other factors that may limit imagery collection, such as clouds for optical imagery. For the "Walrus from Space" project a one month window per population was needed to get cloud-free images of most Atlantic walrus haul-out sites (WWF-UK 2023). Extended time-windows increase the risk of double counting, given that walruses can move between the imaged haul-out sites, which needs to be accounted for when estimating abundance. For large-scale surveys, we recommend that the largest known haul-out sites (i.e. >1000+ for Atlantic walruses and > 10 000 + for Pacific walruses) be prioritized in a batch design, capturing images from them in a tight time frame.

Monitoring walruses from space

Merging walrus conservation needs and Earth observation satellites capabilities, we discuss below the feasibility of monitoring changes in walrus distribution and population trends, with the aim that it be used as a guide for future research using satellite imagery to study walruses.

Distribution shifts

Monitoring shifts in walrus distribution requires *a priori* knowledge regarding where walruses currently haul-out on land (Fischbach et al. 2016, Cubaynes et al. 2026) and to survey these known locations, as well as extending the search to other places where walruses could be hauled out. Monitoring walruses hauled out on sea ice would also be helpful to report changes in distribution. However, the latter is more challenging because this habitat is quite dynamic and walruses tend to be dispersed when on sea ice. Therefore, surveying would have to cover large expanses of sea ice. Specific terrestrial haul-out sites are more predictable. In practical terms, walrus distribution shifts can be evaluated by conducting presence-absence surveys at known terrestrial haul-out sites and beyond these areas to find new haul-out sites. It is important to note that newly discovered haul-out sites may be previously unknown sites rather than newly used sites. Satellites that continuously collect imagery (e.g. Sentinel-2, PlanetScope) could be used to assess past distribution, within the time-frames of operation for given satellites (e.g. 2017 for Sentinel-2, and 2016 for PlanetScope).

Concerning methods of detection using satellite imagery, we recommend using optical satellite imagery due to the higher confidence in the observations. SAR satellites might be helpful if surveying a cloudy region, but it will likely only work for areas with smooth, flat substrates, such as sand and gravel beaches, where walruses stand out from the topography. Validation of SAR on various substrates is needed before this technology can be used systematically. Medium resolution is enough to detect large haul-out groups (likely above 1000 walruses; Fischbach et al. 2025), but VHR satellites will be required to detect smaller groups and individuals with confidence. Studies that have detected walruses in optical satellite imagery have used manual interpretation of the imagery and focused on known haul-out sites. Artificial Intelligence (AI) methods are currently under development, which will facilitate expanded searches for walruses in new locations. Manual review methods either use one or multiple experts or citizen scientists, who visually detect walruses in images, typically based on their distinctive colouration and tendency to gather in tight herds (Boltunov et al. 2012, 2021; Zinglersen et al. 2020, Fischbach and Douglas 2021, Matthews et al. 2022, Sherbo et al. 2023, WWF-UK 2023, Cubaynes et al. 2024). When experts are reviewing the imagery, we recommend a minimum of two observers. For citizen science projects, the optimal number of observers remains to be determined, which is one of the aims of the “Walrus from Space” project. The benefit of citizen science projects is the potential to speed up the analysis of large amounts of imagery, but this remains to be verified, as it requires time from the experts before, during and after the campaign to ensure the task is as engaging and straightforward as possible, intense advertising to recruit volunteers (LaRue et al. 2020), and expert validation of detections.

The inclusion of information related to the size of the detected walrus haul-out groups can refine our understandings in distribution shifts, by looking at changes in areas of importance (those occupied by large numbers of walruses). This would involve estimating absolute counts or measuring the area occupied by walruses hauled out on land, if it is not possible to discern individual animals (see section below for details on counting walruses in satellite imagery).

Population trends

Establishing walrus population trends using satellite imagery will rely on the ability to detect (see section above) and count walruses at their terrestrial haul-out sites to build time series of abundance estimates. Methods to count walruses from space will vary depending on the density of animals at the haul-out site (Fig. 3), which in turn depends on population size, haul-out terrain, openness of surrounding habitat (Altukhov et al. 2024). For sparse haul-out groups, each individual walrus can be counted (i.e. direct estimated count); by placing a point on each animal in the image to ensure no double-counting. Cubaynes et al. (2024) used this method and recommended use of a native resolution of 30 cm or below to produce accurate counts and cautioned against using AI generated 15 cm resolution imagery, as this uplifting process creates artefacts, leading to false detections (Fig. 4). For highly clumped haul-out groups, when individual walruses cannot be discerned at currently available satellite imagery resolution, we recommend drawing an outline around the herd to obtain the area covered by walruses and multiplying it by the density or range of published densities for tight groups (estimated from aerial or drone survey), to get an estimate (Sherbo et al. 2023, Sauvé et al. 2024, Fischbach et al. 2025). Similar to detecting walruses in satellite imagery, we recommend a minimum of two experts to count walruses. Initiatives, such as the “Walrus from Space” project, are testing whether citizen scientists can be used to accurately count walruses in satellite imagery and whether precision metrics based on inter-observer variability across a large pool of citizen scientists could be used to bracket count estimates with appropriate error (WWF-UK 2023, Cubaynes et al. 2024).

At present, counting walruses or outlining herd perimeters is only feasible with VHR satellites and with optical imagery, with some exceptions for large walrus herds hauling out on sand and gravel beaches. TIR satellites with VHR capabilities are not yet available for civil applications. SAR imagery with very high spatial resolution could potentially become useful to enumerate walruses, but its accuracy and efficiency need to be trialled, particularly for haul-out herds with a few hundred individuals or less, and for haul-out sites with rocky shores, and sand/gravel beaches with boulders. It may be feasible to produce estimated counts of walruses using high and medium spatial resolution imagery, but with increased uncertainties (Fischbach et al. 2025). As uncertainty is

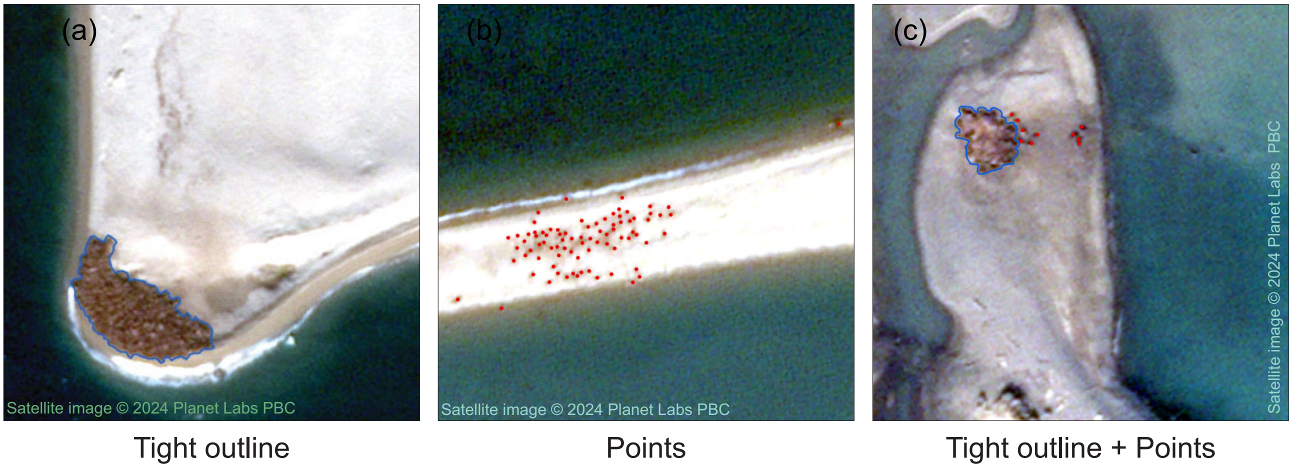


Figure 3 Different approaches to count walruses in very high resolution optical satellite imagery (SkySat satellite imagery; satellite image © 2024 Planet Labs PBC), (a) a tight outline (blue line) to be drawn around tight haul-out herds from which a count is extrapolated by using density estimates, (b) points (red dots) to be placed on top of each individual walruses for sparse haul-out herds, and (c) for herds with tight groups and some walruses spread out, a tight outline should be drawn around the tight group and the walruses outside of that group should be labelled individually.

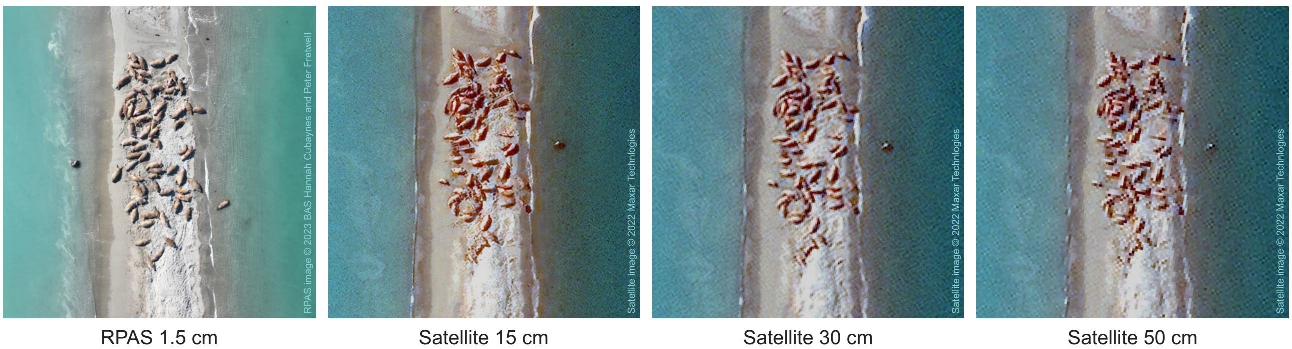


Figure 4 Visual comparison of a walrus herd hauled out at Sarstangen, Svalbard, Norway, images taken using a remotely piloted aircraft system (RPAS) captured 15 min before an optical satellite image (WorldView-3), presented here at three spatial resolution (15 cm AI generated, 30 cm, 50 cm) and adapted from Cubaynes *et al.* (2024). RPAS image © 2023 BAS Hannah Cubaynes and Peter Fretwell, Satellite image © 2023 Maxar Technologies.

inherent in estimates of walrus numbers using satellite imagery, any research publishing walrus counts from space should be transparent on where the uncertainties arise (e.g. where the outline of a walrus herd is in a 10 m resolution image). Ideally, all known haul-out sites would be monitored, but VHR imagery comes at a cost, limiting the geographic extent and/or the frequency of surveys. We therefore suggest identifying a subset of areas for regular counting to document trends, although changes in walrus numbers at these chosen sites could be confounded by small scale distributional changes.

Estimating the density of walruses in satellite imagery (e.g. low, medium, or high density) might be feasible using the colour of the haul-out group. For instance, a haul-out group with a darker brown colour could mean higher density, as opposed to light brown indicating lower densities. However, a number of variables can affect walrus body colouration, such as air temperature and how long walruses have been hauled out. It is well known that walruses that have just come out of the water tend be light in colour (grey or pink), as opposed to walruses that have been hauled out for longer period of time, which can appear reddish brown. Therefore, we encourage using an aerial or drone survey, whenever it is possible to calibrate satellite images, and aim for a near-simultaneous survey because walrus haul-out groups can be dynamic and the area occupied can vary within hours (Fischbach and Douglas 2021, Matthews et al. 2022, Sherbo et al. 2023, Cubaynes et al. 2024). Alternatively, density estimates can be gained from haul-out camera traps, positioned at high enough vantage point to avoid obscuring walruses in oblique photos.

Important considerations when enumerating walruses in satellite imagery include the risk of double counting and the time of day the image was collected. Ideally, a synoptic survey of the whole distribution range for the population or stock (for hunt management) would be conducted with satellite imagery collected nearly simultaneously over all known haul-out sites in the surveyed area. However, this is not feasible in practice, even if using all satellites in operation. Therefore, to mitigate the risk of double counting, implementing distance/time buffers between haul-out sites could be used. In Canada, a buffer of 45 km/day between haul-out sites has been used as a cut-off for independence of counts between adjacent sites (Stewart et al. 2014, Hammill et al. 2016), based on telemetry data showing that this was the farthest distance walruses are expected to travel in a day. If satellite imagery cannot be collected within the distance/time criterion set for adjacent haul-out sites, alternative correction factors should be employed. The time of day that a satellite image is captured will impact the number of walruses counted. For example, early in the morning, calves tend to shelter near their mother for warmth (Fay 1982) and may not be discernible in satellite imagery.

Estimating walrus abundance using satellite imagery might require some adjustments to how we deal with counts for aerial surveys, if we aim to use both methods simultaneously or compare results directly. Traditionally, only walruses deemed "hauled out" are counted, defined as those with their back out of the water, which includes all animals on land and those in shallow water. This is because tags with wet/dry sensors, placed on the back of walruses, are used to assess the proportion of walruses on land *versus* in the water and later used for adjusting raw counts on land to estimate abundance. However, this will be difficult to ascertain visually in satellite imagery and it may be that only walruses on land should be counted, which will require adjustments in the correction factors. Currently, most aerial studies use a correction factor of 0.25–0.30 (i.e. 25%–30% of the walruses are hauled out; Lydersen et al. 2008, Kovacs et al. 2014, Hammill et al. 2016), although haul-out proportions are highly variable (Heide-Jørgensen et al. 2014) and might change, as walrus modify their hauling out pattern in response to reduced summer sea ice (Born et al. 2021). We therefore recommend continued collection of telemetry data, focusing on (a) both sexes and all age groups to avoid biases due to different hauling out patterns (e.g. preference to haul-out on sea ice instead of land in the summer; Monson et al. 2013, Kovacs et al. 2014), and (b) on regions with sparse telemetry data (e.g. Franz Josef Land, Russia). Even in data-rich regions, there is a need to continue tagging animals intermittently to understand how walruses are responding to climate change, although sensitivities regarding tagging walruses need to be carefully considered for hunted populations, especially if it involves drugging the animals, which is not typically supported by Indigenous communities who rely on walrus for their food security.

Counting walruses in the water or hauled out on sea ice may also help overall abundance estimates but they will require their own correction factors (e.g. proportion of walruses at the surface vs. those too deep to be visible (or under ice) that could be estimated using tags fitted with a depth sensor) and an increase in the spatial coverage of the surveys, which is already a limiting factor. There will be instances where counting walruses on sea ice will be preferable to counting walruses on land, such as in regions where sea ice is present year-round (e.g. east coast of Ellesmere Island, Canada) during the summer given walrus's preference for this habitat, or to survey winter use of polynyas. In these situations, the capabilities of satellite imagery to survey larger regions than is possible with aerial surveys could be complementary.

Next steps

Further development is needed to detect, count, and estimate abundance of walruses in satellite imagery. We provide detailed recommendations for future work in Table 2. Future directions for monitoring walruses from space include:

a. continuing to investigate the application of freely available medium resolution (e.g. Sentinel-2) and low-cost high resolution (e.g. PlanetScope) optical imagery;
b. continuing to investigate the application of SAR imagery;
c. assessing the usefulness of citizen science projects to detect and count walruses in satellite imagery;
d. testing the feasibility of using satellite imagery to count walruses on sea ice by selecting an area of interest across which walrus counts and densities are estimated.
e. investigating the use of thermal imagery (e.g. HOTSAT constellation) for detecting walruses on ice, particularly to extend monitoring into winter to study winter use of polynyas;
f. developing occupancy models to better understand haul-out site dynamics, which could be built into habitat suitability models. Over time, this will allow for assessment of distributional changes based on environmental conditions, which is crucial given the current rapid changes of their habitat;
g. assessing the historical use of haul-out sites using archival imagery, potentially from the Planet archive (2016 onward) or Sentinel-1 and-2 archive (respectively 2014 and 2015 onward);
h. using satellite imagery to monitor walrus presence at haul-out sites otherwise difficult to access, to support mitigation efforts to reduce the risk posed by increasing vessel traffic, to manage tourism disturbance, and to investigate the effects of pre- and post- ship activity on walruses;
i. developing standardized annotation protocols and, where possible, make image and annotation datasets openly available, to facilitate development of automated detection and counting approaches (including model benchmarking and reproducibility); and
j. developing automated or semi-automated methods to detect herds or individual walruses in satellite imagery. This will enable monitoring over larger spatial extents, a comprehensive analysis of archival data (especially from high and medium resolution optical image archives), and support regular near-real time monitoring of haul-out sites in the future. We recommend exploring machine learning and deep learning models for automated walrus detection, combined with expert manual review to maintain quality control and quantify uncertainty. Multi-modal data fusion (multiple spatial resolution and multiple type of sensors) should also be considered to improve detection in cloudy or lowlight conditions, and at different spatial resolutions.

Conclusion

Remote sensing, and particularly satellite imagery, is seen as an important tool for walrus monitoring in the future. Such images can provide knowledge on distribution shifts and population trends. Many walrus haul-out locations are in remote regions and are poorly studied because they are logistically difficult to reach using conventional platforms, such as boats and planes. VHR optical imagery holds the greatest potential to detect walrus herds of various sizes to assess distribution shifts, produce accurate counts, and ultimately provide abundance estimates and population trend data. However, its use is currently limited by the cost of acquiring imagery and cloud cover. Therefore, we advise investigating the use of freely available imagery, such as high and medium optical satellite imagery (e.g. PlanetScope, Sentinel-2), where larger groups of walruses can be detected (i.e. estimated herd size of 100 + walruses, and potentially larger). Although optical imagery is more intuitive to interpret, we also suggest trialling

Table 2 Recommendations for monitoring walruses from space.

Satellite imagery collection	
1.	Collect satellite imagery of the known terrestrial haul-sites, as walruses tend to come back to the same places, allowing for comparison between years.
2.	Collect satellite imagery during the summer when sea ice concentration is low and walruses tend to haul-out on land.
3.	The imagery collection window should be as short as possible, weather permitting, and the larger known haul-out sites be prioritized.
Detecting walruses from space	
4.	Use optical satellite imagery, as it is more intuitive to interpret, but SAR imagery should be considered for cloudy regions.
5.	Use satellites with a medium resolution (e.g. Sentinel- 2 with 10 m) to detect haul-out groups of 100 + walruses, but for smaller groups very high-resolution satellites are required.
6.	A minimum of two experts should review the imagery (the critical mass of persons remains to be determined for citizen science projects).
Counting walruses from space	
7.	Be transparent on where the uncertainties related to the count are when publishing walrus satellite imagery counts.
8.	Use very high-resolution optical satellite imagery with a native resolution of 30 cm or below to produce more accurate count. We caution against using modified 15 cm resolution satellite imagery, as they create artefacts (SAR may potentially be useful too but needs to be trialled).
9.	For sparse haul-out groups, each individual walrus should be counted, such as by placing a point on each animal in the image, requiring very high spatial resolution satellite imagery.
10.	For clumped groups, we recommend drawing an outline around the herd to obtain the area covered by walruses and multiply it by the density or range of published densities for tight groups (estimated from aerial or drone surveys), to get an estimated count.
11.	To mitigate the risk of double counting, implementing a distance buffer (e.g. 45 km) between nearby haul-out sites over a given day could be used.
12.	Use an aerial or drone survey, whenever it is available, to calibrate satellite image counts, and aim for a near-simultaneous survey because walrus haul-out groups can be dynamic and the area occupied can vary within hours.
Estimating walrus density from space	
13.	Record the density, whenever a drone or aerial survey is being conducted, to complement the existing library of published densities.
14.	Install camera traps at a selection of key haul-out sites, where the topography is suitable to calibrate density in satellite imagery, and to study daily variation in density.
Estimating walrus abundance from space	
15.	Regarding establishing population trends, we suggest identifying a consistent subset of areas that could produce repeated counts to investigate trends.
16.	Adapt aerial survey methods to estimate abundance in satellite imagery (i.e. counting walruses hauled out on land only and using wet/dry tag data to calculate correction factors to include walruses in the water).
17.	Conduct telemetry studies focusing on all age and sex groups, and particularly on younger males or females as these data are currently lacking and are needed to adjust correction factors for abundance estimates.

the use of SAR and TIR imagery, particularly for monitoring cloudy areas and during periods of darkness. Assessing how the different types of imagery (optical, SAR, and TIR) and spatial resolution (very high, high, and medium) can be combined, may also provide useful insights and solutions to monitoring walruses from space.

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Author contributions

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Conflicts of interest

None declared.

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Data availability

The Atlantic walrus haul-out site database is available on the Conservation of Arctic Flora and Fauna (CAFF) Arctic Biodiversity Data Service at the following link: https://geo.abds.is/geonetwork/89053f0c-79e8-4d54-86a4-6557db4ae0f9 (Cubaynes et al. 2026).

References

Aerts LAM, McFarland AE, Watts BH *et al.* Marine mammal distribution and abundance in an offshore sub-region of the northeastern Chukchi Sea during the open-water season. *Cont Shelf Res* 2013;**67**:116–26. https://doi.org/10.1016/j.csr.2013.04.020

Alaska Science Center. *Synthetic Aperture Radar (SAR) Satellite Images of a Walrus Haulout in Russia*. 2022. https://www.usgs.gov/media/images/synthetic-aperture-radar-sar-satellite-images-a-walrus-haulout-russia (24 July 2025, date last accessed).

Altukhov AV, Kryukova NV, Trukhanova IS *et al.* Enhancing the accuracy and efficiency of Pacific walrus (*Odobenus rosmarus divergens*) surveys: a comparison of visual and aerial imagery-based counts at coastal haulouts. *PLoS One* 2024;**19**:e0307416. https://doi.org/10.1371/journal.pone.0307416

Attard M, Phillips RA, Bowler E *et al.* Review of satellite remote sensing and unoccupied aircraft systems for counting wildlife on land. 2024;**16**:627.

Boltunov A, Evtushenko N, Knijnikov A *et al. Space Technology for the Marine Mammal Research and Conservation in the Arctic: Results of the Pilot Project to Develop Methods of Finding Walruses on Satellite Images*. Murmansk: WWF-Russia 2012;12.

Boltunov AN, Semenova VS, Sokolov AA *et al.* Newly detected haul-out of Atlantic walruses (*Odobenus rosmarus rosmarus*) on Yamal Peninsula has become the biggest in the Kara Sea. *Polar Biology* 2021;**44**:2077–83. https://doi.org/10.1007/s00300-021-02942-0

Born EW, Gjertz I, Reeves RA. *Population Assessment of Atlantic Walrus (Odobenus Rosmarus Rosmarus L.)*. Oslo: Norsk Polarinstitutt, 1995.

Born EW, Wiig Ø, Olsen MT. *Chapter 13–The Future of Atlantic Walrus in a Rapidly Warming Arctic*. London, UK: Elsevier, Academic Press, 2021;309–32.

Burn DM, Cody MB. Use of satellite imagery to estimate walrus abundance at Round Island, Alaska. *Proceedings of the 16th Biennial Conference on the Biology of Marine Mammals*. San Diego, CA, USA, 2005;46.

CAFF. *State of the Arctic Marine Biodiversity Report*. Akureyri, Iceland: Conservation of Arctic Flora and Fauna International Secretariat, 2017.

Cautin IJ, Last KS, Bluhm BA *et al.* High uptake of sympagic organic matter by benthos on an Arctic outflow shelf. *PLoS One* 2024;**19**:e0308562. https://doi.org/10.1371/journal.pone.0308562

Cubaynes HC, Forcada J, Kovacs KM *et al.* Walruses from space: walrus counts in simultaneous remotely piloted aircraft system versus very high-resolution satellite imagery. *Remote Sens Ecol Conserv* 2024;**10**:584–96. https://doi.org/10.1002/rse2.391

Cubaynes HC, Fretwell PT, Bamford C *et al.* Whales from space: four mysticete species described using new VHR satellite imagery. *Marine Mammal Sci* 2019;**35**:466–91. https://doi.org/10.1111/mms.12544

Cubaynes HC, Matthews CJD, Garde E *et al.* Atlantic walrus haul-out site database. 2026. CAFF - Arctic Biodiversity Data Service.https://geo.abds.is/geonetwork/89053f0c-79e8-4d54-86a4-6557db4ae0f9

Dowman I, Jacobsen K, Konecny G *et al. High Resolution Optical Satellite Imagery*. Caithness: Whittles Publishing 2012.

eoPortal. *Satellite Missions Catalogue*. 2024. https://www.eoportal.org/satellite-missions?Mission+type=EO (15 August 2025, date last accessed).

ESA. Sentinel-2 user handbook. 2015.

European Space Agency. *S1 Mission: Geographical Coverage*. 2025. https://sentiwiki.copernicus.eu/web/s1-mission(7 October 2025, date last accessed).

Fay FH. Ecology and biology of the Pacific walrus, *Odobenus rosmarus divergens* Illiger. *North American Fauna* 1982;**74**:1–279. https://doi.org/10.3996/nafa.74.0001

Fischbach AS, Douglas DC. Evaluation of satellite imagery for monitoring pacific walruses at a large coastal haulout. *Remote Sens* 2021;**13**:4266. https://doi.org/10.3390/rs13214266

Fischbach AS, Douglas DC. *Researchers Turn to SAR Satellite Imagery to Monitor Pacific Walruses as Ice Melt Increases in the Arctic*. 2022. https://www.capellaspace.com/blog/researchers-turn-to-sar-satellite-imagery-to-monitor-pacific-walruses-as-ice-melt-increases-in-the-arctic(24 July 2025, date last accessed).

Fischbach AS, Kochnev AA, Garlich-Miller JL *et al. Pacific Walrus Coastal Haulout Database, 1852–2016—Background Report* U.S. Geological Survey Open-File Report 2016, p. 27.

Fischbach AS, Taylor RL, Douglas DC. *Monitoring Pacific Walrus Coastal Haulouts by Satellite to Estimate Herd Abundance and Distribution*. Wildlife Society Bulletin, 2025;e1614.

Fischbach AS, Taylor RL, Jay CV. Regional walrus abundance estimate in the United States Chukchi Sea in autumn. *J Wildlife Manag* 2022;e22256. https://doi.org/10.1002/jwmg.22256

Garde E, Hansen RG. Chapter 4–Stocks, distribution and abundance. *The Atlantic Walrus*. London, UK: Elsevier, Academic Press, 2021;77–95.

Grebmeier JM, Overland JE, Moore SE *et al.* A major ecosystem shift in the northern Bering Sea. *Science* 2006;**311**:1461–4. https://doi.org/10.1126/science.1121365

Hammill MO, Mosnier A, Gosselin J-F *et al. Estimating abundance and total allowable removals for Walrus in the Hudson Bay–Davis Strait and South and East Hudson Bay Stocks during September 2014*.DFO Can. Sci. Advis. Sec. Res. Doc. Report number: 2016-036. 2016:v + 37.

Hansen RG, Boertmann D, Rosing-Asvid A *et al.* Current abundance of walrus in East Greenland. Report SC/25/14-WWG/07 for NAMMCO Scientific Committee Working Group on Walrus. Copenhagen, The Netherlands: NAMMCO, 2018;17.

Hauser DDW, Laidre KL, Stern HL. Vulnerability of Arctic marine mammals to vessel traffic in the increasingly ice-free Northwest Passage and Northern Sea Route. *Proc Natl Acad Sci* 2018;**115**:7617–22. https://doi.org/10.1073/pnas.1803543115

Heide-Jørgensen MP, Laidre KL, Fossette S *et al.* Abundance of walruses in eastern Baffin Bay and Davis Strait. *NAMMCO Sci Publ* 2014;**9**:159–78. https://doi.org/10.7557/3.2606

Higdon JW. *Walrus Haulouts in the Eastern Canadian Arctic: a Database to Assist in Land Use Planning Initiatives*. A report and GIS database by Higdon Wildlife Consulting, Winnipeg, MB, on behalf of WWF-Canada, Iqaluit, NU, for submission to the Nunavut Planning Commission, Cambridge Bay, NU. 2016;18.

Jay CV, Marcot BG, Douglas DC. Projected status of the Pacific walrus (*Odobenus rosmarus divergens*) in the twenty-first century. *Polar Biol* 2011;**34**:1065–84. https://doi.org/10.1007/s00300-011-0967-4

Keighley X, Olsen MT, Jordan P *et al. The Atlantic Walrus: Multidisciplinary Insights into Human-Animal Interactions*. London, UK: Elsevier, Academic Press 2021.

Khan CB, Goetz KM, Cubaynes HC *et al.* A biologist's guide to the galaxy: leveraging artificial intelligence and very high-resolution satellite imagery to monitor marine mammals from space. *J Mar Sci Eng* 2023;**11**:595. https://doi.org/10.3390/jmse11030595

Kim Y-H, Min S-K, Gillett NP *et al.* Observationally-constrained projections of an ice-free Arctic even under a low emission scenario. *Nat Commun* 2023;**14**:3139. https://doi.org/10.1038/s41467-023-38511-8

Kochnev AA. Phenology of the Pacific Walrus (*Odobenus rosmarus divergens*) in coastal waters of Wrangel Island: the impact of the sea ice dynamics. *Biol Bull Russian Acad Sci* 2019;**46**:1156–64. https://doi.org/10.1134/S1062359019090061

Kovacs KM, Aars J, Lydersen C. Walruses recovering after 60+ years of protection in Svalbard, Norway. *Polar Res* 2014;**33**:26034. https://doi.org/10.3402/polar.v33.26034

Kovacs KM, Belikov S, Boveng P *et al. 2021 State of the Arctic Marine Biodiversity Report (SAMBR), Update: Marine Mammals*. Akureyri, Iceland: Conservation of Arctic Flora and Fauna International Secretariat 2021.

Kovacs KM, Lemons P, MacCracken JG *et al.* Walruses in a time of climate change. *Arctic Report Card 2015* 2015;66–74.

Kovacs KM. *Odobenus Rosmarus*. 2025. www.iucnredlist.org (11 February 2026, date last accessed)

Kryukova NV, Kruchenkova EP, Ivanov DI. Killer whales (*Orcinus orca*) hunting for walruses (*Odobenus rosmarus divergens*) near Retkyn Spit. Chukotka. *Biol Bull Russian Acad Sci* 2012;**39**:768–78. https://doi.org/10.1134/S106235901209004X

Laidre KL, Stirling I, Lowry LF *et al.* Quantifying the sensitivity of Arctic marine mammals to climate-induced habitat change. *Ecol Appl* 2008;**18**:S97–125. https://doi.org/10.1890/06-0546.1

LaRue M, Brooks C, Wege M *et al.* High-resolution satellite imagery meets the challenge of monitoring remote marine protected areas in the Antarctic and beyond. *Conserv Lett* 2022;**15**:e12884. https://doi.org/10.1111/conl.12884

LaRue MA, Ainley DG, Pennycook J *et al.* Engaging 'the crowd' in remote sensing to learn about habitat affinity of the Weddell seal in Antarctica. *Remote Sens Ecol Conserv* 2020;**6**:70–8. https://doi.org/10.1002/rse2.124

Lowry L. *Odobenus Rosmarus. The IUCN Red List of Threatened Species 2016: E.T15106A45228501*. 2016. https://doi.org/10.2305/IUCN.UK.2016-1.RLTS.T15106A45228501.en (31 July 2024, date last accessed).

Lydersen C, Aars J, Kovacs KM. Estimating the number of walruses in Svalbard from aerial surveys and behavioural data from satellite telemetry. *Arct* 2008;**61**:119–28.

Lydersen C. Walrus terrestrial haul-out dataset in Svalbard. Norwegian Polar Institute. 2008. https://doi.org/10.21334/NPOLAR.2008.788AC8FE

This isLynch HJ. Satellite remote sensing for wildlife research in the polar regions. *Mar Technol Soc J* 2023;**57**:43–50. https://doi.org/10.4031/MTSJ.57.3.1

Matthews CJD, Dispas A, Mosnier A. *Evaluating Satellite Imagery for Atlantic Walrus (Odobenus Rosmarus Rosmarus) Stock Assessment-a Pilot Study*, Canadian Technical Report of Fisheries and Aquatic Sciences. Report 3492. 2022:v +25.

McCandless SW, Jackson CR. Chapter 1. Principles of synthetic aperture radar. *Synthetic Aperture Radar Marien User's Manual*. Washington, DC, US: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Office of Research and Applications, 2004;1–24.

Mikkelsen L, Kovacs KM, Blanchet MA *et al.* Interannual site fidelity by Svalbard walruses. *Sci Rep* 2024;**14**:15822. https://doi.org/10.1038/s41598-024-66370-w

Monson DH, Udevitz MS, Jay CV. Estimating age ratios and size of Pacific walrus herds on coastal haulouts using video imaging. *PLoS One* 2013;**8**:e69806. https://doi.org/10.1371/journal.pone.0069806

NASA. *Synthetic Aperture Radar (SAR)*. 2025. https://www.earthdata.nasa.gov/learn/earth-observation-data-basics/sar (11 February 2026 date last accessed).

Niemi A, Bluhm BA, Juul-Pedersen T *et al.* Ice algae contributions to the benthos during a time of sea ice change: a review of supply, coupling, and fate. *Front Environ Sci* 2024;**12**:1432761. https://doi.org/10.3389/fenvs.2024.1432761

PAME. *The Increase in Arctic Shipping, Arctic Shipping Status Report #1*. Arctic Council, 2025. https://oaarchive.arctic-council.org/items/01ddf449-9048-4d6a-a056-65303831bb63 (11 February 2026 date last accessed).

Planet. *Education and Research Program*. 2024. https://www.planet.com/industries/education-and-research/#:∼:text=Any%20university%2Daffiliated%20student%2C%20faculty,to%20PlanetScope%20and%20RapidEye%20imagery. (27 June 2024, date last accessed).

Planet. *PlanetScope*. 2023. https://developers.planet.com/docs/data/planetscope/ (19 January 2024, date last accessed).

Rantanen M, Karpechko AY, Lipponen A *et al.* The Arctic has warmed nearly four times faster than the globe since 1979. *Commun Earth Environ* 2022;**3**:168. https://doi.org/10.1038/s43247-022-00498-3

Rees WG. *Physical Principles of Remote Sensing*. Cambridge: Cambridge University Press, 2013.

Sauvé C, Mosnier A, St-Pierre AP *et al. Abundance Estimate of the South and East Hudson Bay Walrus (Odobenus Rosmarus Rosmarus) Stock from an Aerial Survey Flown in September 2022*. DFO Canadian Science Advisory Secretariat Research Document. Report 2024/034. 2024:iv + 12.

Semenova V., Boltunov A., Nikiforov V. Key habitats and movement patterns of Pechora Sea walruses studied using satellite telemetry. *Polar Biology*, 2019;**42**:1763–1774. https://doi.org/10.1007/s00300-018-02451-7

Sherbo BAH, Iacozza J, O'Hara A *et al.* Validation of satellite imagery for quantitative population assessment and monitoring of Atlantic walrus. *Remote Sens Appl: Soc Environ* 2023;**32**:101065. https://doi.org/10.1016/j.rsase.2023.101065

Stewart REA, Born EW, Dietz R *et al.* Estimates of minimum population size for walrus near southeast Baffin Island, Nunavut. *NAMMCO Sci Publ* 2014;**9**:141–57. https://doi.org/10.7557/3.2615

Udevitz MS, Jay CV, Taylor RL *et al.* Forecasting consequences of changing sea ice availability for Pacific walruses. *Ecosphere* 2017;**8**:e02014. https://doi.org/10.1002/ecs2.2014

USGS. *Landsat Satellite Missions*. 2024.https://www.usgs.gov/landsat-missions/landsat-satellite-missions (27 June 2024, date last accessed).

Wiig Ø, Born EW, Stewart REA. Management of Atlantic walrus (*Odobenus rosmarus rosmarus*) in the arctic Atlantic. *NAMMCO Sci Publ* 2014;**9**:315–42. https://doi.org/10.7557/3.2855

WWF-UK. *Walrus from Space*. 2023. https://www.wwf.org.uk/learn/walrus-from-space (18 August 2023, date last accessed).

Yurkowski DJ, Brown TA, Blanchfield PJ *et al.* Atlantic walrus signal latitudinal differences in the long-term decline of sea ice-derived carbon to benthic fauna in the Canadian Arctic. *Proc. R. Soc. B. Biol. Sci.* 2020;**287**:20202126. https://doi.org/10.1098/rspb.2020.2126

Zinglersen KB, Garde E, Langley K *et al. RemoteID: Identification of Atlantic Walrus at Haul out Sites in Greenland Using High-Resolution Satellite Images Greenland Institute of Natural Resources in Collaboration with Asiaq Greenland Survey 2 Title: RemoteID. Identification of Atlantic Walrus at Haul out Sites in Greenland Using High-Resolution Satellite Images*. Greenland: Greenland Institute of Natural Resources 2020;62.

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