JNCC Report 753

Exploring VHR satellite imagery as a tool for monitoring cetaceans around the UK and Overseas

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January 2024

ISSN 0963 8091

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This report should be cited as:
Norman, D., Clear, N., Clarke, P., Taylor, N.L. & Banga, R. 2024. Exploring VHR satellite imagery as a tool for monitoring cetaceans around the UK and Overseas. *JNCC Report 753*, JNCC, Peterborough, ISSN 0963-8091.
https://hub.jncc.gov.uk/assets/fdc172a1-c319-4586-a7db-841eb2beaeba

Acknowledgments:
Specialist expertise was kindly provided by Hannah C. Cubaynes from the British Antarctic Survey. Satellite imagery used in the case studies were accessed via Maxar's Digital Globe archive. Whale sightings information used for the case studies were accessed from Sea Watch Foundation and the Online Recording Kernow and Scilly websites.

EQA:
Internal quality assurance was provided by Roma Banga and Nikki Taylor.
This report is compliant with JNCC's Evidence Quality Assurance Policy
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Executive Summary

This report reviews recent developments in the use of very high resolution (VHR) satellite imagery for monitoring cetacean species, namely larger bodied whales, and trials the technique on three case study areas within UK waters and the Overseas Territories, comparing against verified observations of whale species at the same time and location. Recommendations for further research and development have been provided to enable the application of VHR satellite imagery as a monitoring tool for large-bodied whales.

Very high resolution (VHR) satellite imagery offers the potential to compliment traditional methods for monitoring large whale species. Advances in satellite imagery technology have led to images with an on-the-ground resolution of 30 cm, and development of new satellites capable of 10 cm resolution which improve the ability to accurately detect the presence of large whales. The use of these data could compliment other monitoring techniques, helping to cover remote areas, cover large spatial and temporal scales and reduce impacts from disturbance.

The use of satellite imagery for whale monitoring has innate challenges which need to be considered including the negative impact of cloud cover, rough seas, turbidity of water and other environmental factors that affect detectability of whales in imagery. Satellites capture an image or series of images which are a snapshot in time, which means whale species which spend less time at the surface such as deep divers, have a lower probability of being detected. The morphology, behaviour, and position of the whale in the water, at the moment the image was captured, also impact the likelihood of detection, increasing perception bias.

The management and processing of VHR imagery can be computationally expensive, requiring large digital storage solutions and high processing power. Currently, the process of scanning images for potential whale-like objects is best performed manually which is labour intensive, but there are number of automated and semi-automated approaches being developed which would significantly streamline the process. To enable these automated processes, there is a need for reference images to train machine learning models. Currently there are relatively few of these reference images available and no central repository or sharing process in place to enhance the availability of imagery for this purpose.

Satellite imagery is owned mainly by commercial entities, many of whom make their image archives available for use through online portals or geographic software. Many offer free access for research but involve costs for any other uses. Existing programmes which provide free access to satellite imagery do not currently include imagery at high enough resolution to be used for whale monitoring. However, these programmes could offer a framework to improve the accessibility of these images in future.

Further research is needed to test and further develop detectability for more species and across different locations, and to address inherent bias to work towards obtaining accurate abundance and density estimates via this method. Therefore, currently VHR imagery is not a viable replacement for traditional surveys but may offer a complimentary method for detecting occurrence of larger cetacean species in remote areas where conditions are favourable.

Summary of recommendations

- Further investigate the minimum size of cetaceans which can be identified from VHR imagery, especially as high-resolution imagery becomes available.
- Pilot the use of VHR images for cetacean detection in a range of scenarios and locations.
- Further investigate whether counts from satellite imagery can be used for population and density estimates, including the effects of availability and perception bias, and develop methods to minimise these effects.
- Assess and account for factors limiting accurate detection, including trialling the use of wider spectrum imagery.
- Establish best practice and approaches for data collection and analysis for using VHR imagery for wildlife monitoring, including facilitating data access and sharing.
- Further develop and research the automation and semi-automation of processing satellite imagery.

Contents

1. Introduction

Evidence of abundance, distribution, and migratory patterns is vital to understand the conservation status and management needs of mobile species (Paxton *et al.* 2016; Hammond *et al.* 2021; Geelhoed *et al.* 2022). These data can be particularly difficult to collect for cetaceans, which spend much of their life under water and are widespread throughout our oceans (Bamford *et al.* 2020). Traditional offshore cetacean monitoring techniques consist of observations from ships, aircraft, or land-based vantage points, but these methods can be costly, labour intensive and limited in scope due to species' large ranges (Fretwell *et al.* 2014; Borowicz *et al.* 2019). They typically involve significant logistical lead times (Bamford *et al.* 2020), require highly trained personnel and can cause disturbance to the target species, which require specific survey and statistical techniques to correct for inherent bias (Vukelic *et al.* 2018; Hammond *et al.* 2021). Challenges in accessing remote areas can result in surveys that are biased towards those regions which are easily accessible and hence 'appear' to be more used by cetaceans than those regions that are not frequently monitored (Bamford *et al.* 2020). Development and application of new and complimentary techniques for effective monitoring of these species is therefore a priority to ensure that sufficient and appropriate evidence is available to both report on status and as a basis for effective management decisions.

As remote sensing tools become increasingly accessible, the use of very high resolution (VHR) satellite imagery (where each pixel represents less than 1 m of the ground) offers an opportunity to complement traditional methods to fill some of the current knowledge gaps in large whale spatial and temporal distribution and population dynamics (Cubaynes *et al.* 2019; Höschle *et al.* 2021).

For this project, a literature review was conducted to collate evidence of the application of satellite imagery for monitoring cetaceans. This included a review of the data sources of satellite imagery and associated costs of accessing and utilising these data; a feasibility review for the use of freely available VHR satellite imagery; and a review of the challenges and opportunities associated with the use of VHR satellite imagery for marine mammal monitoring. Application was then tested with a series of case studies with known large whale presence and a review of available imagery.

A scoping exercise was also conducted to investigate the potential use of VHR satellite imagery as a potential monitoring tool for two large whale species at three pilot sites; by comparing validated observations to satellite imagery captured at the same location and within a reasonable time window of the observation.

2. Satellite imagery terminology

Remote sensing or 'Earth observation' using satellites can be either *active* – which emit their own source of illumination and use sensors to measure the reflection; or *passive*; which measure reflected sunlight. Passive optical imagery is the principal form of satellite imagery explored in this report. Optical imagery is captured light within the visible and infrared wavelengths of the electromagnetic spectrum. There are key aspects of satellite imagery which impact the application in the case of large whale detection:

2.1 Spectral resolution

Spectral resolution refers to the number of wavelength 'bands' in the image, whereby each band represents a section of the electromagnetic spectrum. Optical satellite imagery typically consists of a panchromatic image (a single band, grayscale image) and a multispectral image, comprising multiple bands where the amount of light energy captured within each band is recorded for each pixel. Typically, bands for optical imagery are within the red, green and blue spectrums, and may also include near infra-red. When viewing these images or performing analysis, certain bands or combinations of bands provide greater contrast between features of interest and the background. For example, Fretwell *et al.* (2019) used near infrared (NIR) imagery to identify stranded whales as a method of distinguish the carcass, which appears in a pinkish hue, from other features on the coastline, such as vegetation, logs, rocks and waves.

2.2 Spatial resolution

A key aspect of satellite imagery when being used for the detection of animals is the *spatial resolution*. This is defined by the relative area of the ground represented by one pixel on the image. For example, at a spatial resolution of 1 m, each pixel would represent an area of size 1 m x 1 m on the ground. A higher spatial resolution increases pixel density per area of ground and results in a more detailed image. Very high resolution (VHR) satellite imagery is defined as imagery with 1 m resolution of less than 1 m (sub 1 m), or where 1 pixel of the image represent less than 1 m of the Earth's surface.

2.3 Pan sharpening

Pan sharpening is a process where the detail in the higher resolution panchromatic pixels is used to increase the resolution of the lower resolution multispectral pixels, by creating a single multispectral image. This process increases the image spatial resolution of the multispectral image to provide more information to discern a target feature with confidence (Charry *et al.* 2021). It should be noted that some pan sharpening algorithms reduce eight band imagery to four band imagery (red, green, blue and infrared). For the data analysis conducted in this review, the authors used either the Gram-Schmidt or ESRI pan sharpening algorithms.

2.4 Archival imagery

Archival imagery are data images which are over approximately 90 days old and are regularly provided through a different access process than more recent images. In some cases, archival imagery is available to search on provider websites and are cheaper to acquire than tasking a satellite to take images at a specific time and location. The majority of archived satellite images are focused around high interest areas such as areas of human conflict, or terrestrial or coastal habitats (Höschle *et al.* 2021), therefore archived catalogues of images covering open sea areas are scarce compared to terrestrial areas (Rodofili *et al.* 2022).

2.5 Satellite tasking

Where imagery is required for a specific location and/or within a specific time range, a satellite can be '*tasked'* or ordered to capture imagery. However, this service can be costly, and it can be challenging to instantly task a satellite due to factor such as access prioritisation (prioritisation of high-paying customers); satellite revisit rates (the rate at which a satellite returns to the location of interest); and cloud cover. A request to task a satellite needs to be made in advance with enough time for the satellite to be in the correct position to capture images. As a result, there are limitations as to how quickly images can be procured, which impacts how they can be used.

3. Application of satellite imagery in large whale monitoring

A literature review was conducted to provide an overview of developments and examples of the use of satellite imagery for cetacean monitoring to date. The review aimed to compare the different approaches and imagery sources documented in peer-reviewed studies, and to discuss the caveats and considerations in using satellite imagery to monitor cetacean presence and distribution.

A search was performed of the Web of Science database for '(cetacean* OR whale*) AND "satellite image*"' to identify papers to review. A review of the title and abstracts resulted in 19 papers found, and a further a review of the references used within these papers, identified an additional five papers, totalling 24 publications to review (see Table 5, Appendix 1).

3.1 Considerations for selecting species, study sites and imagery

There are several aspects which need to be considered when using VHR imagery as an option for monitoring large marine mammals. Below is a summary of the key considerations recorded in the literature.

- The suitability of the location and the environmental conditions:
  - Above water variables such as cloud cover and sea surface conditions can impact detectability of features in the imagery (Höschle *et al.* 2021).
  - Sub-surface variables such as turbidity due to sediment patterns and algal blooms can impact detection of features below the surface (Fretwell, Staniland and Forcada, 2014).
- The density and species of animals present:
  - Morphological distinction of the target species to enable species' identification, such as distinctive features (e.g. humpback pectoral fins) (Cubaynes *et al.* 2019).
  - Season: imagery collected close to known peaks in seasonal abundance is likely to yield improved results. This is more of a consideration during trialling phases for the use of this technology for monitoring.
- The typical behaviour exhibited by the whales present and how this could impact on their detectability.
- The costs of accessing, managing, and scanning the imagery.
- Whether there was a need to run additional monitoring to validate or compliment the satellite imagery.

To date, nine species have been reported in the literature as having been successfully detected in VHR satellite imagery. The smallest of these are the beluga whale (*Delphinapterus leucas*) and narwhal (*Monodon monoceros*), both with a maximum length of 5.5 m (Charry *et al.* 2021). Additionally, a study by Ramos *et al.* (2022) used satellite imagery to detect bottlenose dolphin (maximum length 4 m) using circles marks in the seabed sediment created by the dolphins during specific foraging behaviour. In this example, the presence of mud rings made identification of individual dolphins possible, demonstrating that some behaviours can increase probability of detection in some circumstances. These studies are summarised in Table 1.

Studies have generally focussed on known abundance hotspots, with particular emphasis on sheltered areas with calm waters and low swell in which the whales aggregate to breed or feed, to help improve the probability of detection. Low densities of target species and open water areas which are susceptible to rough water and swell decrease the likelihood of detecting whale presence, and areas with multiple whale species present pose challenges to positive species' identification.

Not all study locations had positive whale detections. Guirado *et al.* (2019) were unable to detect feeding and/or migratory humpback whales on the Peruvian or Japanese coast, nor fin whales feeding in the Canary Islands. Leaper *et al.* (2015) were also unable to detect blue whales off the south coast of Sri Lanka due to confusion with waves.

Table 1: Summary of studies applying satellite data to monitor whales.

Species	Location	Suitability commentary	Studies
Beluga whale (*Delphinapterus leucas*)	Herald Island, Wrangel Island Reserve, Arctic	Limited human presence at the site is thought to reduce the potential for errors in confusion between whale and non-whale objects.	Platonov *et al.* (2013)
	Cumberland Sound Nunavut, Canada	Animals present for their entire life cycle for this population, potential to monitor breeding success. Narwhals are very rarely seen in this area, reducing chance of species' identification error	Charry *et al.* (2021)
	Cook Inlet, Alaska	Animals are present for their entire life cycle for this population	Khan *et al.* (2023)
Blue whale (*Balaenoptera musculus*)	South coast, Sri Lanka	Relatively calm seas with low swell during survey time period, decreasing the impact of environmental factors on detection. Largest species which increases likelihood of positive identification, but these animals spend less time at the surface, increasing availability bias.	Leaper & Fretwell (2015)
Bottlenose dolphin (*Tursiops truncatus*)	Chetumal-Corozal Bay, Mexico and Belize	Behaviour used to identify animal presence – obvious mud rings created through specific foraging behaviour	Ramos *et al.* (2022)
	Florida Bay, USA		

Species	Location	Suitability commentary	Studies
Bowhead whale (*Balaena mysticetus*)	Herald Island, Wrangel Island Reserve, Arctic	Lack of human activity in the site is thought to reduce the potential for errors in animal identification. Species spends more time at the surface, decreasing availability bias.	Platonov *et al.* (2013)
Fin whale (*Balaenoptera physalus*)	Pelagos Sanctuary, Mediterranean Sea	Calm seas with low swell, increasing the likelihood of positive detection.	Cubaynes *et al.* (2019); Cubaynes & Fretwell (2022)
Gray whale (*Eschrichtius robustus*)	Laguna San Ignacio, Mexico	Breeding ground, increased density of animals increases likelihood of detection. Small, enclosed bay with low swell, decreasing the impact of environmental factors on detection.	Cubaynes *et al.* (2019); Cubaynes & Fretwell (2022)
	Baja California, Mexico	Breeding ground, increased density of animals increases likelihood of detection	Guirado *et al.* (2019)
Humpback whale (*Megaptera novaeangliae*)	Au'au Channel, Maui Nui, Hawaii	Breeding ground from December to April, with a peak in February to March; high density of animals increases likelihood of detection. Low swell area, decreasing the impact of environmental factors on detection.	Abileah (2002); Borowicz *et al.* (2019); Cubaynes *et al.* (2019); Guirado *et al.* (2019); Bamford *et al.* (2020); Cubaynes & Fretwell (2022)
	Gerlache Strait, Western Antarctic Peninsula	Summer feeding ground for cetaceans, high density of animals increases likelihood of detection. Humpbacks account for more than 80% of the sightings, reducing the challenge of species' identification.	Bamford *et al.* (2020)
	Coral Sea, Australia	Breeding ground, high density of animals increases likelihood of detection.	Guirado *et al.* (2019)
	Kimberley region of Western Australia	Breeding ground, high density of animals increases likelihood of detection.	Thums *et al.* (2018)

Species	Location	Suitability commentary	Studies
Narwhal (*Monodon monoceros*)	Baffin Bay, Nunavut, Canada	Summer aggregation in large numbers, high density of animals increases likelihood of detection. Beluga are rarely seen in this area, reducing chance of species' identification error	Charry *et al.* (2021)
North Atlantic right whale (*Eubalaena glacialis*)	Cape Cod Bay, Massachusetts, USA	Winter/spring feeding ground, high density of animals increases likelihood of detection. Skim-feeding behaviour at the surface, increasing the likelihood of detection.	Hodul *et al.* (2023; Khan *et al.* (2023)
Sei whale (*Balaenoptera borealis*)	Gulf of Penas, Patagonia, Chile	Focused on a known mass mortality event. Heavily vegetated and complex coastline, introduces a challenge	Fretwell *et al.* (2019); Clarke *et al.* (2021)
Southern right whale (*Eubalaena australis*)	Golfo Nuevo, Peninsula Valdes, Argentina	Nursery ground between July and November, high density of animals increases likelihood of detection. Sheltered bay, decreasing the impact of environmental factors on detection.	Fretwell *et al.* (2014); Cubaynes *et al.* (2019); Borowicz *et al.* (2019); Guirado *et al.* (2019); Cubaynes & Fretwell (2022)
	Witsand, South Africa	Breeding ground, high density of animals increases likelihood of detection.	Guirado *et al.* (2019); Cubaynes & Fretwell (2022)
	Enderby Island area, Auckland, New Zealand	Breeding ground, high density of animals increases likelihood of detection. Sheltered from wind, decreasing the impact of environmental factors on detection.	Guirado *et al.* (2019); Cubaynes & Fretwell (2022); Höschle *et al.* (2022)
	Imbituba county, Brazil	Breeding ground, high density of animals increases likelihood of detection.	Corrêa *et al.* (2021)

3.2 Accessing imagery

Almost all satellites presently capable of capturing VHR imagery are commercially owned by companies such as Maxar, Planet and Airbus (Morrison 2020; Cubaynes *et al.* 2023), with the exception of the Cartosat-3 satellite which is owned by the Indian government (Höschle *et al.* 2021). This means the costs of tasking satellites for imagery for a specific purpose can be high, but the element of competition regulates these costs to a degree. This remains one of the most significant barriers to broad application of this data source.

After a prescribed period, tasked satellite images are considered as archived and made available either directly or through third parties. Archival imagery is cheaper to acquire than tasking a satellite to collect imagery at a specific time and location. Archival images are made available for use either as a free service; free as a trial basis; for specific work such as research; or on a commercial pay-to-use basis. As satellites are not constantly collecting imagery and therefore only capture images when tasked, the majority of archival satellite images are focused around high interest areas, such as areas of human conflict, or terrestrial or coastal habitats (Höschle *et al.* 2021). Therefore, an archived catalogue of imagery covering open sea areas is scarce compared to terrestrial areas (Rodofili *et al.* 2022).

A limited amount of VHR satellite imagery is available for free via Google Earth or the ESRI World Imagery Layer, which is accessible through GIS software such as ArcGIS or QGIS. Google Earth comprises satellite and aerial imagery, including some commercially available satellite imagery, such as from Maxar, and focuses its efforts on updating satellite imagery of the places undergoing the most change (i.e. land development projects, Schottenfels 2020). Freely available archives of aerial and satellite imagery, such as Google Earth, reduce the geospatial information and spectral resolution to RGB rather than eight bands (Höschle *et al.* 2021). A reduced spectral resolution decreases the information in the image, as well as limiting any spectral and visual analyses to only those RGB bands.

ESRI's World Imagery Layer offers satellite imagery from Maxar displayed at 0.3 m resolution in some metropolitan areas globally, 0.5 m resolution in the continental United States and parts of Western Europe, and at 1 m elsewhere. Lower resolution imagery is also provided by the US Geological Survey and Earthstar Geographics, as well as some aerial imagery made available through the GIS community (ESRI 2021). Borowicz *et al.* (2019), Corrêa *et al.* (2021), Guirado *et al.* (2019) and Ramos *et al.* (2022) have successfully used Google Earth Pro to detect whales in the VHR satellite imagery in well-known whale hotspots. However, despite detections being successful, the use of this platform for monitoring in a marine environment is generally limited in terms of ocean coverage and restricted to some coastal areas (up to approximately 4 km offshore) (Guirado *et al.* 2019), where there is variation in temporal frequency and low resolution of the images (Appendix 3).

There are several freely available secondary sources of satellite imagery, such as LandSat and Sentinel. However, these services would not be classed as VHR. The resolution of the imagery is too coarse for marine mammal detections, but may have a role in monitoring marine environmental conditions. For instance, the Copernicus Programme provides free, full and open access to most of the data produced by the programme, comprising upwards of 30 satellites (Copernicus 2021). The highest spatial resolution for optical imagery that the Copernicus Programme satellites capture is 10 m.

Most studies listed above sourced archival imagery from Maxar captured by either the WorldView-2 or WorldView-3 satellites (see Tables 2 and 3). In the case of Leaper and Fretwell (2015) and Thums *et al.* (2018), imagery was obtained through tasking of the WorldView-2 and WorldView-3 satellites, respectively. For studies investigating the use of machine learning to automate detection, aerial imagery or artificially augmented satellite images have been used to supplement available data for annotated training datasets. For example, Borowicz *et al.* (2019) and Corrêa *et al.* (2021) used aerial imagery as a training dataset for machine learning approaches for the detection of large whales, and tested the model using satellite imagery. Ramos *et al.* (2022) used free satellite imagery acquired from Google Earth, and Guirado *et al.* (2019) used Google Earth in combination with freely available aerial images from Arkive (now no longer available), NOAA Photo Library and NWPU-RESISC45 (a freely available benchmarking dataset for machine learning classification).

The following tables of satellite imagery sources (Tables 2 and 3) summarise sources provided either from the literature, suggested in personal communication with experts or identified via a systematic internet search (i.e. Google). Note that these tables are not exhaustive.

Table 2: Direct VHR Satellite imagery sources and the studies in which their imagery had been used. Spatial resolutions have been included for both panchromatic (pan) and multispectral (multi) imagery where possible.

Name	Description	Satellites and studies in which applied

Maxar	• Offer a one-month free trial
	• Satellites:
	  • IKONOS (0.8 m) – decommissioned
	  • QuickBird (multi 0.65 m) – decommissioned
	  • GeoEye-1 (pan 0.41 m, multi 1.65 m)
	  • WorldView-1 (pan only, 0.5 m)
	  • WorldView-2 (pan 0.46 m, multi 1.95 m)
	  • WorldView-3 (pan 0.31 m, multi 1.24 m)
	  • Worldview-4 (pan 0.3 m, multi 1.24 m) - decommissioned
	• Launching WorldView Legion constellation of six satellites in 2021 (pan 0.29 m, multi 1.16 m), but imagery is anticipated in 2023.
	• Offer a subscription service for optical, radar and analysis ready imagery as well as base maps.
	Discovery Maxar offers public online access to archived satellite imagery.
	SecureWatch offers download access to archived Maxar imagery on a subscription bases.
	Maxar operate GeoHIVE, which is a crowdsourcing platform for annotation and validation of features of interest in imagery.
		GeoEye-1: Platanov *et al.* (2013)
		WorldView-2: Fretwell *et al.* (2014); Leaper & Fretwell (2015); Fretwell *et al.* (2019); Thums *et al.* (2018); Khan *et al.* (2023)
		WorldView-3: Cubaynes *et al.* (2019); Borowicz *et al.* (2019); Bamford *et al.* (2020); Cubaynes & Fretwell (2022); Hodul *et al.* (2023); Khan *et al.* (2023)

Name	**Description**	**Satellites and studies in which applied**
Planet	• Offer a 14-day free trial • Two VHR satellite constellations: ○ SkySat (pan 0.58–0.86 m, multi 0.72–1 m) ○ Pelican (multi 0.3 m) • Future resource in Pelican constellation of up to 32 satellites and 0.3 m resolution, with launch planned for 2023.	
Airbus	• Pléiades constellation of two satellites (0.5 m) • Pléiades Neo (0.3 m) constellation of six satellites launched in 2021 and 2022 – the first European satellite constellation at this resolution. • Vision (2 m multi and 0.9 m pan) • Also offer radar imagery – TerraSAR-X GeoStore and One Atlas give access to airbus archival imagery.	Corrêa *et al.* (2021)
Albedo Space Corporation	Constellation of 24 satellites 0.1 m panchromatic satellite and multispectral 0.4 m, planned first launch in 2024, with full constellation planned for 2027	-

Table 3: Secondary VHR Satellite imagery sources and the studies in which their imagery had been used. Spatial resolutions have been included for both panchromatic (pan) and multispectral (multi) imagery where possible.

Google Earth/Pro	• Map formed from aerial and satellite imagery from multiple sources, including Maxar • Images are red-green-blue (RGB) rather than 8-band • Google Earth Pro allows for search of historical imagery	Corrêa *et al.* (2021); Guirado *et al.* (2019); Borowicz *et al.* (2019); Ramos *et al.* (2022)
ESRI World Imagery Layer – ArcGIS	• Features Maxar imagery at 0.3 m resolution for select metropolitan areas, 0.5 m resolution across the US and parts of Western Europe, and 1 m resolution imagery everywhere else. • This can also be added as a layer to other GIS platforms, such as QGIS.	-

Sentinel Hub – EO browser	• Sentinel, Landsat and other Earth observation imagery • Subscription plans available • Free to download analytical data with EO browser for non-commercial use • Free archive access of Sentinel-1 (radar, 5 x 20 m), Sentinel-2 (10 m), and Landsat 5, 7 and 8 (30 m), plus others measuring sea surface topography and temperature, or atmospheric measurements • Provide paid access to commercial third-party data: Airbus SPOT (pan 1.5 m, multi 6 m) and Pléiades (pan 0.5 m, multi 2 m), and PlanetScope (3 m) • There are free accounts and commercial data packages available for research and pre-commercial exploitation/validation sponsored by ESA. There is a step-by-step guide available on how to apply.	-
European Space Agency (EPS) PDGS-DataCube	• New service that provides access to Earth observation imagery and derived data products, including third-party missions, such as Airbus Pléiades • Offers storage space and processing power for analyses	-
Ireland National Geospatial Data Hub	National Geospatial Data Hub is a crowdsourcing platform in Ireland for annotation and validation of features of interest in imagery.	-

3.3 Costs

3.3.1 Satellite imagery

Each provider has their own guidance for pricing formats, so the costs of access can vary considerably between providers, products, and customer organisation types, and are likely to change over time. Generally, archival imagery is less expensive than tasked imagery. Maxar, Planet and Airbus all provide quotes to customers based on the area and time of interest; as a result, published prices were unavailable for this report.

However, as an example, Fretwell *et al.* (2019) reported the costs for accessing Maxar imagery at the time of their journal submission. This example of the costs, below, was found to be comparable to aerial survey in some areas but may be more cost-efficient in remote or hard to access areas such as open ocean.

- Archive:
    - 0.5 m resolution: \$17.50 per km^2 / 0.3 m resolution: \$22.50 per km^2
    - Discounts were available at the following rates:
        - research/education: 30%
        - NGOs: 5%
        - US federal Government: 50%
    - The minimum area that could be ordered was 25 km^2.
- Tasking:
    - 0.5 m resolution: \$27.50 / 0.3 m resolution: \$32.50
    - Some areas of the world (about 10% – high demand countries) were charged at a higher rate.
    - The minimum area that could be ordered was 100 km^2.
    - Where an image is considered cloudy (containing more than 20% cloud), the customer does not have to purchase it, but may receive a discount if they do.

3.3.2 Storage and processing

An additional cost associated with satellite imagery is the software, hardware and/or computing power required to store and analyse large datasets. For this project alone, imagery acquired as part of case study 2 (Falkland Islands) comprised 75 GB of data for a total area of 2,060 km^2. Any pixel or spectral analyses would likely require higher computing power, and any larger study areas would require additional storage, both of which would incur additional costs where these are not already available.

Where necessary, services are available which provide computing power and data storage solutions to meet these needs. Online or cloud storage solutions such and super computational services are widely available but involve a level of ongoing cost and can vary by supplier and customer type.

3.4 Imagery scanning methods

Manual scans of features of interest are primarily performed on pan sharpened images (Bamford *et al*. 2020; Cubaynes *et al*. 2020; Fretwell *et al.* 2019, 2014). This consisted of a systematic visual search of the image by one or more reviewers to classify any features of interest according to the confidence in the feature identification. For large marine mammals, feature classifications vary slightly among studies but typically consisted of 'water', 'definite whale', 'probable whale', 'possible whale', 'other' (i.e., boat, rock, sea birds), or 'unclassified'. Where images were corrected for the top of atmosphere or radiometrically corrected, ENVI image processing software has been used (Fretwell *et al.* 2014; Cubaynes *et al.* 2019; Fretwell *et al.* 2019).

Features such as colouration, flippers and flukes are more clearly visible (Cubaynes *et al.* 2019; Hodul *et al.* 2023) and help distinguish whales from other non-whale objects. Other evidence of whale presence can also be detected at 0.31 m resolution imagery, such as after-breach, fluke print, wake, contour, blow and defecation (Cubaynes *et al.* 2019), or marks in the surrounding environment created during specific behaviour (Ramos *et al.*

2022). These features, along with size and colouration, help to identify features of interest as whales or otherwise.

To reduce the time needed to process satellite imagery for whale detections, Borowicz *et al.* (2019), Cubaynes *et al.* (2019), Fretwell *et al.* (2019, 2014), Guirado *et al*. (2019), Höschle *et al.* (2022) and Leaper and Fretwell (2015) used automated or semi-automated approaches for detection and feature classification; using rule-based pixel analysis, object-based image analysis or machine learning approaches. Borowicz *et al.* (2019) used the PyTorch deep learning framework to implement a convolutional neural network (CNN). Guirado *et al.* (2019) used Google TensorFlow deep-learning framework for step one of their process and Google TensorFlow object detection API.

Fretwell *et al.* (2014) compared the following automatic pixel-based approaches to detect southern right whales in 0.5 m resolution images:

1. Maximum likelihood supervised classification: user inputs signatures of pixel values for each class and the algorithm segregates pixels into classes accordingly.
2. Unsupervised classification: the image is classified into its component parts based only on the information held within the image via two algorithms:
    a. isoData: uses clustering algorithm to determine natural groupings of cells.
    b. K-means: pixels are iteratively clustered into nearest feature classes using a minimum-distance technique.
3. Thresholding of bands: The authors used histograms of whale Digital Number (DN) values as a guide to build thresholds that maximised the ratio of multiple pixels to single pixels. Whales, unless submerged, should present as multiple pixels due to their size. By working iteratively to formulate the thresholds, the authors could maximise the signal (suspected whale) and reduce noise (false positives).

This study concluded that thresholding the single bands (approach 3), delivered the closest match to the manual count, and was subsequently used by Leaper and Fretwell (2015).

Cubaynes *et al.* (2019) also used spectral analysis by extracted spectral radiances; RGB and near-infrared (NIR) for each pixel of whale-like objects, water and non-whale objects. Here radiances were compared across four whale species (fin, gray, humpback and southern right whales) and with their surrounding water. The analysis showed that the radiance values for grey and fin whales were more easily distinguished from water than humpback and southern right whales. This study demonstrated non-whale objects were clearly discernible from whale-like objects for some species and that this approach could be used in an automated detection system.

Borowicz *et al.* (2019) and Guirado *et al.* (2019) considered the application of machine learning to automate classification. Borowicz *et al.* (2019) trained CNNs on down-scaled aerial imagery of minke whales from video and tested the performance of the CNN on 0.31 m resolution satellite imagery containing humpback and southern right whales. The tested CNNs preformed with a high degree of accuracy, but the authors acknowledged that additional classes, such as boats, planes, etc., would increase the accuracy of the CNN as the algorithm wouldn’t be forced to classify non-whale features into either “water” or “not whale”. A refined version of the resulting algorithm from Borowicz *et al.* (2019) as tested by Höschle *et al.* (2022) on automated detection of southern right whales, showed a high degree of compatibility with data from vessel surveys captured within a 12 hour window.

Guirado *et al.* (2019) applied a two-step process to a combination of freely available aerial and satellite imagery. The method was able to confirm the presence of whales in 6 of the 10 assessed whale hotspots and resulted in a classification performance of 78% ± 0.07%. The first CNN classified images as ‘whale’, ‘ship’, or ‘water and submerged rocks’. The images classified as whale were then passed to the second CNN, which annotated each whale with a bounding box. This method was tested on 10 whale hotspots using imagery that coincided with known whale watching periods. Each hotspot was a known habitat for one of four whale species: fin, grey, humpback and southern right whales.

The CNN model developed through this research is the basis for a whale survey commercial service; ‘SPACEWHALE’. Höschle *et al.* (2022) further tested the SPACEWHALE algorithm for southern right whale detection in comparison to vessel-based observations and found comparable results from both methods.

Currently, manual scanning is the most accurate method for image analysis (Rodofili *et al.* 2022). A review on remote sensing techniques for marine mammal observation highlighted the ineffectiveness of pixel-based automation to give accurate counts of individuals (Rodofili *et al.* 2022). Current recommendations suggest the use of object-based image analysis, thresholding and CNN methods as future development for the use the VHR satellite imagery for whale detection (Cubaynes *et al.* 2019; Clarke *et al.* 2021; Rodofili *et al.* 2022).

3.5 Challenges and limitations

3.5.1 Accessibility of images

A major challenge in the use of VHR satellite imagery for large whale monitoring, are the barriers to accessing existing imagery, and the costs associated with tasking satellites (Charry *et al.* 2021; Clarke *et al.* 2021).

Tasking a satellite provides the best option in terms of gathering targeted images of a specified location within a given time frame but is also the most expensive avenue. Archival images, while cheaper to obtain, are limited in terms of open water coverage, since there is little demand for coverage of offshore locations. Existing applications have mainly been terrestrial or coastal, and vary in temporal coverage, so may not be suitable for monitoring in the required locations. Large whales have been detected in VHR imagery, but the limited availability of imagery in terms of open ocean coverage and the variation in temporal resolution is exacerbated and presents a challenge for establishing effective monitoring practices.

Existing partnerships which are well established for lower resolution imagery, such as Copernicus Programme Planet and the European Space Agency’s “Education and Research Partnership” and the GAIA (Geospatial Artificial Intelligence For Animals) initiative provide a framework for how VHR satellite imagery could be made more widely available for research moving forward (Clarke *et al.* 2021; Khan *et al.* 2023). Programmes such as these could also support the development of a catalogue of annotated images for training of machine learning approaches for scanning images for whale-like features (Khan *et al.* 2023).

3.5.2 Scanning Methods

The manual scanning method is accurate but tedious and time consuming; with an average/approximate time of 3 hours 20 minutes taken to scan 100 km^2 (Cubaynes *et al.* 2019). Where it is necessary to survey large areas of water, manual annotation may not be feasible, particularly if the survey is repeated regularly (Borowicz *et al.* 2019; Khan *et al.* 2023).

Automating the image scanning process can drastically reduce the time required to cover large areas. However, automation for detection of marine mammal species in satellite imagery is in its infancy and there are considerable challenges which would need to be addressed before these techniques can be routinely applied (Clarke *et al.* 2021; Khan *et al.* 2023). Research in detection automation is advancing quickly, however, including the use of artificial intelligence for automated whale detection as an emerging technique (Kapoor *et al.* 2023). Automation in the form of machine learning, is also inhibited by limited availability of annotated satellite imagery required for 'training datasets (Höschle *et al.* 2021; Khan *et al.* 2023).

Training a CNN requires a dataset of labelled images depicting different species and postures, environmental conditions and possible confounding features such as ships and rocks (Borowicz *et al.* 2019; Guirado *et al.* 2019; Höschle *et al.* 2022). Machine learning techniques have the potential to compensate for smaller training datasets for the use of CNN (Kapoor *et al*. 2023). These techniques use augmentation tools on available imagery to artificially increase datasets. Clarke *et al.* (2021) and Höschle *et al.* (2021) recommend the creation of an open-source database of labelled whale images with an appropriate coding framework to facilitate more robust training of automated systems, the development of pre-processing workflows, and the refinement of species' identification; and to test the ability of developed models to detect whales across different environmental conditional and locations, considering factors limiting detectability.

In automated approaches, misclassifications yield false positives (e.g. water or non-whale features such as boats or rocks classified as whale) and false negatives (e.g. whale classified as water or a non-whale feature). There is therefore still a requirement for a semi-automated approach or 'human-in-the-loop' review of positive detections to remove false positives, assuming no false negative, or a quantification of the number of false positives so that this can be accounted for during analysis (Höschle *et al.* 2021).

3.5.3 Detectability

Whether performing a manual scan or using an automated approach, challenges with detectability remain. Accurate detection requires a contrast between the animal and the environment, but Cubaynes *et al.* (2019) found some whale species to have a similar spectral profile shape to their habitat, suggesting a purely pixel-analysis approach to detection is unlikely to be effective. Low contrast between whales and water was also shown to decrease CNN performance in Guirado *et al.* (2019).

The majority of satellite tasking is presently concentrated over terrestrial areas, which greatly restricts the availability of archival open-ocean imagery (Borowicz *et al.* 2019; Khan *et al.* 2023). Where there is imagery available, the requirement for low percentage cloud cover with little to no white caps (Cubaynes *et al.* 2019) further reduces the volume of suitable imagery, and priority for tasking satellites is often given to high paying customers (Clarke *et al.* 2021; Khan *et al.* 2023). Choppy water or sea swell refracts sunlight (Fretwell *et al.* 2014) and sea spray creates "noise" that can be difficult to differentiate from whales (Borowicz *et al.* 2019), impairing both detection and accurate counts. This has led to confusion between whales and waves, sea foam, or other objects such as boats, rocks, and seabird aggregations (Fretwell *et al.* 2014).

Detectability can also be impacted by whale behaviour, and there are inconsistencies across the literature, varying between species and locations. Cubaynes *et al.* (2019) found an increased confidence in manual detections when the whale was positioned parallel to the ocean surface, whereby the fluke, flippers and shape were visible. For the CNNs, whale behaviours such as 'blowing', 'breaching' and 'peduncle' postures provided better detectability and reduced false negatives, than 'logging' or 'submerged' body positions. Guirado *et al.* (2019) found that the whales could be being confused with submerged rocks or the seafloor when in logging or submerged positions, but also highlight that most of the whales detected in this study were in these passive behaviour positions.

The maximum depth at which a whale can be detected, and the smallest size of whale detectable, are other unknowns. A resolution of 0.31 m usually provides enough detail for large whales, but it is more challenging to detect and count smaller species or calves (Cubaynes *et al.* 2019). Ramos *et al.* (2022) detected bottlenose dolphins in 1.24 m resolution imagery, using sediment marks created during specific feeding behaviour as an indicator, which is the smallest cetacean species detected through VHR satellite imagery to date. Inconsistent whale size in images due to vertical position in the water (e.g. during diving behaviour) adds to the complexity, as does variation in water column penetration due to turbidity and surface roughness (Fretwell *et al.* 2014).

3.5.4 Species' differentiation

Characteristics such as size, colouration and species-specific features can assist with species' identification (Cubaynes *et al.* 2019). However, these characteristics can be difficult to determine from satellite imagery and underestimation of body length may be caused by the visibility of the fluke or the oblique angle of the animal as it ascends or descends in the water column. Species-specific features such as white head callosities can assist with species identification for right whales (Hodul *et al.* 2023), but other features are not equally seen for other species (e.g. colouration) (Cubaynes *et al.* 2019).

3.5.5 Adjustment for biases

Perception bias may arise where there is variation in how objects are classified, and availability bias may occur because of a proportion of whales being too deep to detect (Bamford *et al.* 2020; Charry *et al.* 2021). In Bamford *et al.* (2020), satellite-derived estimates of density were found to have underestimated boat-derived density by a factor of 2.5 in calm conditions, rising to 6.3 in rougher regions. Obtaining reliable density estimates, therefore, requires adjustment for biases.

These inherent biases also exist in traditional imagery-based survey methods but can be accounted for through specific data collection methods and statistical tools which have been developed alongside methodological advances. These techniques to account for bias could similarly be developed and applied to surveys using satellite imagery (Rodofili *et al.* 2022), but require good levels of data to feed into the development and testing (Khan *et al.* 2023).

3.5.6 Computation and data storage

A comprehensive satellite imagery survey would require very large volumes of imagery, which will all need to be annotated. Advances in computing, data storage and associated infrastructure will be needed for the application of this technology (Höschle *et al.* 2021). A collaborative approach at an international scale is required to address the requirements for computational power and data storage, and would be an important step towards the wider use of satellite imagery for whale observations (Clarke *et al.* 2021; Khan *et al.* 2023).

3.6 Potential applications

Very high resolution satellite imagery has the potential to enable the surveillance of marine locations at more frequent intervals than would otherwise be possible, the presence of large whales such as southern right humpback and fin whales have all been detected in Very High Resolution (VHR; sub-meter spatial resolution) satellite imagery (Hodul *et al.* 2023; Bamford *et al.* 2020; Rodofili *et al.* 2022; Clarke *et al.* 2021; Cubaynes *et al.* 2019; Fretwell *et al.* 2019, 2014).

Satellite imagery offers potential benefits such as enabling detection of whales in remote or less accessible areas (Khan *et al.* 2023) or areas of high whale density (Höschle *et al.* 2022). VHR imagery can have comparable costs to traditional survey methods; but may also be more or less costly depending on the situation (Thums *et al.* 2018; Cubaynes 2019; Rodofili *et al.* 2022). Remote sensing removes the disturbance effect of observer presence (Vukelic *et al.* 2018; Rodofili *et al.* 2022), thus minimising changes to animal movement caused by disturbance compared to ship based surveys (Bamford *et al.* 2020). Advances in automating the processing of imagery could further reduce observer cost and effort (Vukelic *et al.* 2018; Clarke *et al.* 2021; Rodofili *et al.* 2022). However, the use of VHR imagery for large whale monitoring has its own challenges and biases which need to be overcome, such as methods for automating detection, correcting for availability bias and costs associated with procuring appropriate imagery (Clarke *et al.* 2021; Höschle *et al.* 2021; Rodofili *et al.* 2022).

There are numerous applications of VHR satellite imagery for monitoring cetacean populations, including the following which were identified in the published literature:

- Strandings: As a compliment to long-term monitoring programmes; to help identify patterns in stranding events, enhance information on temporal and spatial scale of an unusual or mass stranding event. In remote areas, to gather baseline data of occurrences of strandings (Clarke *et al.* 2021).
- Calving areas: to conduct larger surveys over whole areas, where detectability has been successful (Fretwell *et al.* 2014).
- Migratory species: to capture the arrival of migratory species in known areas of use and any changes in use of feeding or breeding areas (Borowicz *et al.* 2019)
- Ship strike: to inform distribution patterns and relative density in and around shipping lanes to help reduce the risk (Leaper & Fretwell 2015).
- Policy: to inform marine spatial planning and priorities for marine biodiversity protection (Guirado *et al.* 2019).

VHR satellite imagery surveys are a complementary tool to existing methods, helping inform planning for aerial or boat surveys by highlighting target areas, and providing continued monitoring where traditional surveys are restricted.

3.7 Future developments

3.7.1 Improving satellite imagery resolution

Satellite companies continue to develop and launch satellites with improving spatial and temporal resolution and new companies forming around the world, in Europe, China, India, and Japan (Morrison 2020). For instance, Airbus launched a constellation of four satellites, Pleiades Neo 3, in April 2021 and 2022, with more launches planned, matching the 0.3 m panchromatic resolution of Maxar's WorldView-3 and (decommissioned) WorldView-4 satellites. Pleiades Neo data is now available for research and development use through a project proposal to the ESA. Maxar launched the first batch of a constellation of six satellite in 2023, WorldView-Legion, which offers a spatial resolution of 0.29 m with an increased revisit rate. Planet also began launching a constellation of up to 30 satellites with 0.3 m resolution called Pelican in 2023. The Albedo Space Corporation have been licenced to launch a satellite constellation capable of capturing 0.1 m panchromatic imagery, between 2024 and 2027.

3.7.2 Automating image scanning

Machine learning methods for automating annotation of the imagery are a key area of future development. Co-funded by the European Space Agency and BioConsult in collaboration with Stony Brook University and HiDef Aerial Surveying Ltd, the SPACEWHALE project aims to provide a commercial service whereby customers define a survey area after which SPACEWHALE source the VHR imagery which is run through their trained CNN to obtain detection information (ESA Space Solutions 2018). Phase two of the project consists of almost simultaneous aerial transect and VHR satellite imagery surveys of the Bay of Biscay to scale up the training database. The aerial survey found fin whales and dolphin species, but the satellite imagery has not yet been reported (European Space Agency 2021). SPACEWHALE claims that it currently costs the same as, or in some cases is cheaper, than traditional surveys and it is likely to become cheaper and more efficient as the satellite technology progresses (European Space Agency 2018). The GAIA initiative, a collaborative initiative with government funded through NOAA, is also planning to use new annotation protocols and tools to develop training datasets for machine learning models.

The incorporation of data from citizen science programmes (where volunteers and members of the public are involved in data collection) to assist with validation of detections, as well as recording sightings for ground-truth data, could also provide a step forward in terms of efficiency and robustness (Vukelic *et al.* 2018).

3.7.3 Synthetic-Aperture Radar (SAR) and other remote sensed data

Besides optical imagery, some satellite sensors are capable of capturing synthetic-aperture radar (SAR) imagery; weather observations; and thermal and altimetry data. SAR imagery is produced using an active sensor that emits a radar pulse, then records the backscatter to produce an image. The imagery is less intuitive to interpret to humans since the light is recorded at microwave or radio wave wavelengths, but it has the advantage of being unaffected by atmospheric conditions such as clouds.

Radar can provide information on sea surface state and turbidity so could assist with identifying time periods of ideal sea conditions in which to acquire higher resolution optical imagery. Thus, SAR imagery could be used to estimate the likelihood of whales being present in an area at specified times to better inform targeted image acquisition. Radar has the additional benefit of being unaffected by cloud so can capture clear imagery in cloudy conditions.

SAR data captured by the Sentinel satellites as part of the Copernicus programme and by the ICEYE satellites which have a spot mode resolution of 1 m (available through ECS PDGS-DataCube) are freely available. Copernicus includes both satellite and in-situ ground data used for validation, both of which are also freely available, alongside analyses performed and maps produced using the data (The European Union Earth Observation programme 2020). As with optical imagery, a spatial resolution of less than 1 m is required for whale detection (Höschle *et al.* 2021), but the freely available SAR data from Copernicus only offers 10 m spatial resolution. However, the ECS PDGS-DataCube included 25 cm SAR captured by the ICEYE radar imaging satellites, which, through image differencing, may have potential for detecting whale strandings or aggregations of live whales.

Maps of ocean colour can show plankton blooms that could indicate areas of higher primary productivity, therefore could help identify potential food hotspots which attract marine predators, including whales. Other remotely sensed data such as that on marine vessel traffic, could also indicate potential disturbance, risk of collision between whales and vessels (ship-strike) and areas and/or times whales are likely to avoid. Data on sea temperature, roughness and turbidity could also inform calculations of detection probability and feed into subsequent corrections for bias.

3.8 Conclusion

The studies reviewed here demonstrate that large whales can be reliably detected and counted manually in VHR satellite imagery (Fretwell *et al.* 2019), where the environmental conditions are favourable. As the resolution of satellite imagery improves, so does the confidence in accurate whale detections. In combination with higher resolution satellite data (Tables 2 and 3) an increase in the revisit rate for sites of interest could enable wider use of this technology in future.

Manual scanning presently remains the most accurate way of detecting and counting whales in satellite images (Höschle *et al.* 2021). But the results from initial machine learning studies are promising, particularly with the current focus on reach and development into this. Studies have demonstrated that CNN-based methods trained on high-quality images can reach good performance on medium-quality images (such as those available from Google Earth) but using higher resolution imagery tends to result in better performance. The advantage of the machine learning approach is that the trained CNNs are transferable to any region or RGB images with different characteristics in colour, lighting, atmospheric conditions, background, or size/shape of target objects.

Archived images allow for hindcasting to assess past occurrence, where imagery is available (Bamford *et al.* 2020). “Noisy” sea conditions have been identified as a confounding factor for satellite imagery surveys, similar to ship- or land-based surveys, and methods are required to account for this in analyses. Whales have been successfully detected in VHR satellite imagery in calm, shallower areas where they aggregate to calve, and the potential for monitoring in these areas is high. Future experimentation and pilot studies are now needed to improve the reliability of satellite imagery-based survey methods, to investigate their potential in open ocean, and to explore how best to combine them with traditional methods (Höschle *et al.* 2021).

Though satellite imagery can accurately detect the presence of large whales, there are several challenges when trying to determine density estimates. Compared with density estimates from a traditional ship-based line-transect survey, Bamford *et al.* (2020) concluded that unadjusted estimates from VHR imagery were considerably lower than from the ship survey, and when adjusted for surface availability and weather conditions, they fell within an order of magnitude. The lower image-based count was expected due to the instantaneous nature of image acquisition, limitations in image resolution, and the potential for random fluctuations in local whale densities between the dates of the boat and satellite surveys (8 to 10 days) (Bamford *et al.* 2020). More research and development would be needed before whale counts from satellite imagery can be used to calculate abundance and density to account for perception and availability bias (Rodofili *et al.* 2022).

VHR satellite imagery could be a useful tool to complement, but not replace, traditional survey methods in remote areas (Fretwell *et al.* 2019; Clarke *et al.* 2021; Khan *et al.* 2023). If the technical and practical challenges discussed above were addressed, a satellite image-based survey could offer an additional tool for monitoring whales in remote or inaccessible areas; save time and costs spent on logistics, acquiring permits and charter, and travel (Cubaynes *et al.* 2019); and offers reduced observer cost and effort, and improved accuracy of population estimates and trends (Fretwell *et al.* 2014). The ability to survey previously under-monitored or difficult to access areas offers the opportunity for researchers to fill existing data gaps and evaluate change. However, there is a need to improve accessibility of

VHR imagery through partnerships and international cross-industry collaborations (Clarke *et al.* 2021; Khan *et al.* 2023).

However, further research is needed to test and further develop detectability for more species and across different locations, and to address inherent bias to obtain accurate abundance and density estimates. Therefore, currently VHR imagery is not a viable replacement for traditional surveys but may offer a complimentary method for detecting occurrence of larger cetacean species in remote areas where conditions are favourable, such as the UK Overseas Territories. There is currently further research and development being conducted which could address the limitations of using satellite imagery for marine mammal monitoring (Clarke *et al.* 2021; Höschle *et al.* 2021).

The use of satellite imagery for monitoring the natural environment and wildlife is an active area of research, and rapid progress is being made. VHR imagery as a tool for monitoring cetacean species may not currently be a feasible option, but this may change in the near future.

4 Case study: trialling the use of satellite imagery as a cost-effective monitoring tool

Studies using VHR satellite imagery to detect whales identified significant limitations in terms of ocean coverage, temporal frequency and spatial resolution. Given these limitations the feasibility and potential application of trial-based WorldView-3 imagery as a monitoring tool in both the UK and in a UK Overseas Territory was explored. For continued use of these imagery, cost of using commercial imagery would need to be considered.

Two case study sites were selected to test the potential application of VHR satellite imagery for monitoring purposes in regions of interest for UK policy. JNCC has provided technical assistance to the UK Overseas Territories for more than 20 years to inform and support their biodiversity and environmental management practices (JNCC 2019a). JNCC fulfils this role both directly through engaging with stakeholders and facilitating regional partnerships within the Overseas Territories and indirectly through scientific advice to the UK Government. Recently, JNCC has been using Earth observation (EO) data to map coastal habitats for the Falkland Islands and collaborate with the Austral Earth Observation Alliance to promote the use of EO data throughout the South Atlantic and South America (Jones 2019).

Sightings and survey data are then used to ground truth two case studies:

1. Large whale presence in UK waters.
    - Humpback whale at St Ives Bay, Cornwall, UK
    - Large whale species at Botallack, Penwith, Cornwall, UK
2. Sei whale presence in the Falkland Islands.

For each case study, existing verified observation records were obtained from citizen science and public sightings hosted by non-government organisations to confirm the presence of the target species for a specific location and date. Corresponding archival VHR satellite imagery for these records were manually scanned, using a systematic search approach as per Cubaynes *et al.* (2019).

For each observation record, an area of interest (AOI) was used to search Maxar's Digital Globe archive for VHR satellite imagery matching the date and location of recorded sightings of the species of interest. The imagery available was filtered by date to match the exact date of the sighting, or within the dates of the survey. The resulting images were then filtered by cloud coverage so that only images with less than 20% cloud over the AOI were included. Matching images were available for preview, with the full resolution images then supplied by Maxar on a free-trial basis.

Full resolution imagery was supplied by Maxar through a File Transfer Protocol (FTP) site with imagery from each study site stored in a separate folder under the given order ID. Each of the study site folders contained files for each of the panchromatic and multispectral images, as well as GIS shape files.

The GIS raster shapefile displays the tile structure for larger images (Figure 1). Each tile is comprised of a .tif file or mosaic of files in both the panchromatic and multispectral imagery folders, with the filename including the row and column number for the tile (e.g. R1C1). For this analysis, the .tif files were used and loaded into ArcMap as raster layers and were processed to improve drawing speed using pyramids and the images were resampled using bilinear interpolation, a technique recommended for continuous data such as satellite imagery.

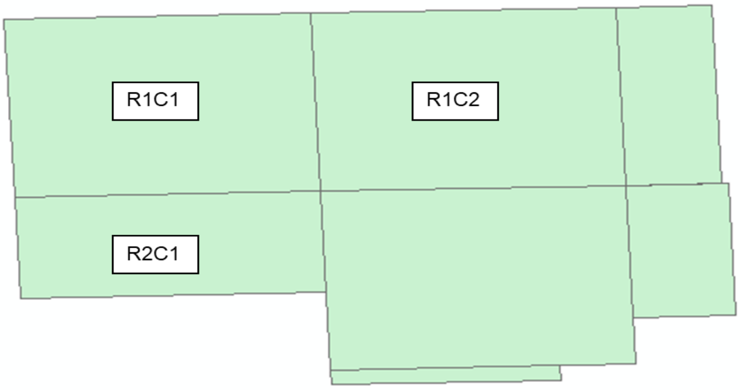

Figure 1: Tiling of imagery for St Ives Bay, with each polygon representing individual .tif raster files. Each tile corresponds to a separate TIF file for each of the panchromatic and multispectral images, with the naming convention referring to row and column number (i.e. R1C1). Labels for tiles in R1C1, R1C2 and R2C1 have been added for illustration.

WorldView-3 imagery, consisting of a 0.31 m spatial resolution panchromatic image and a 1.24 m resolution multispectral image in the eight visible and near infrared (NIR) bands (Table 4), were used for this case study. Following Cubaynes *et al.* (2019) and Bamford *et al.* (2020) satellite imagery processing methods, a panchromatic sharpening technique was run on the multispectral images using the ESRI algorithm in ArcMap version 10.1. To display the images correctly in ArcMap 10.1 and to apply pan sharpening; the red, green and blue bands were selected as bands 5, 3 and 2, respectively. Support for WorldView-3 was added to ArcGIS after version 10.3.1, enabling the .tif file to be loaded with the metadata for the images (such as band order and band width), making processing of these images more efficient in ArcGIS version 10.3 and later.

Table 4: Description of the panchromatic and multispectral bands in WorldView-3 imagery (European Space Agency, no date).

Spectral range	Band number	Band name	Spectral band
Panchromatic	-	-	450–800 nm
Multispectral (VNIR)	1	Coastal blue	400–450 nm
	2	Blue	450–510 nm
	3	Green	510–580 nm
	4	Yellow	585–625 nm
	5	Red	630–690 nm
	6	Red edge	705–745 nm
	7	Near-IR1	770–895 nm
	8	Near-IR2	860–1,040 nm

Once the image was pan sharpened and had been adjusted for optimum display, a visual scan was performed at a 1:1,500 scale, following Cubaynes *et al.* (2019) and Bamford *et al.* (2020). Regions that required further interrogation using a higher zoom level were returned to at 1:500 scale to continue scanning.

4.1 Case study 1: Humpback whales in UK waters

The humpback whale (*Megaptera novaeangliae*) is considered a vagrant species in UK waters and, as such, is protected under Annex IV of the EU Habitats Directive (JNCC 2019b). Recorded observations have been increasing over the last two decades, particularly in Scotland, where fewer than 10 were recorded in 2004 but more than 40 were reported in 2016 (Pix 2018). In a recent study of sightings, movement of humpback whales between their high latitude feeding ground and UK waters was confirmed, with the Firth of Forth in Scotland suggested to be a migratory stopover (O'Neil *et al.* 2019). To date, however, there is insufficient data to inform assessments of the size and quality of the habitat occupied for long-term survival or to inform short-term trends (JNCC 2019b).

4.1.1 Sourcing UK humpback whale sightings data

UK humpback whale sightings between December 2020 and March 2021 were reviewed from two publicly available sources:

- Scottish UK Humpback Catalogue
- Sea Watch Foundation – cetacean sightings in South-west England and South Wales.

The records were checked for the presence of other whale species within the temporal and spatial scope of the study to identify other whale species which may also be present in the area. The sightings reviewed here were not exhaustive; the Sea Watch Foundation sightings are broken down into regional lists on their website and only the one region (South-west England and South Wales) was reviewed for this study.

In relation to the locations within this case study, the Cornwall Wildlife Trust (CWT) run a citizen science project involving local volunteers in regular surveys of marine wildlife in Cornish waters, on which they produce annual reports. The data collected through this project is hosted by the Local Environmental Records Centre (ERCCIS) and is available to view online. The Forth Marine Mammal Project (part of the Whale Dolphin Conservation (WDC) Shore Watch Programme) is active in collecting records of local cetacean sightings in the Firth of Forth on the Scottish east coast, WDC make biological records available through the NBN Atlas. The sighting records used for each of the case study sites are listed in Appendix 2.

The search for archival imagery from Maxar, corresponding to verified humpback sightings around the UK, returned no matches for sightings in Scotland. However, there was one match in St Ives and a sighting of a large whale of unknown species at Botallack, in Cornwall: Image ID 10400100637E9F00.

4.1.2 St Ives Bay, manual scan results

Two overlapping satellite images were captured by the WorldView-3 satellite at 11:17 on 7 December 2020, almost three hours ahead of the recorded humpback whale sighting at 14:00. While the full image contained 41% cloud, cloud covered only 3.3% of the AOI (Figure 2).

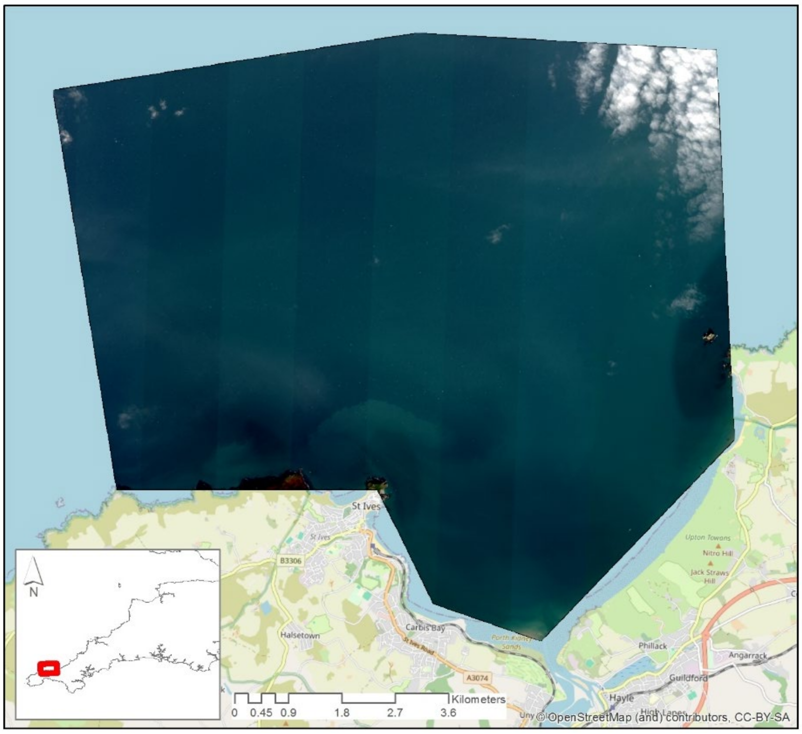

Figure 2: Preview of imagery for the St Ives AOI requested from Maxar. Image ID: 104001006239FF00. Basemap © Open Street Map

Due to the size of the imagery for St Ives Bay (88 km^2), the area was split into seven imagery tiles (Figure 3), and the visual scan was performed on each tile separately. The sea state in the St Ives imagery was showed some areas with more waves visible, with some wavelets and white caps, which can make cetacean detection challenging in traditional survey techniques (Figure 4). The area took 124 minutes to scan at 1:1,500 scale, not including checks of potential features at 1:500 zoom.

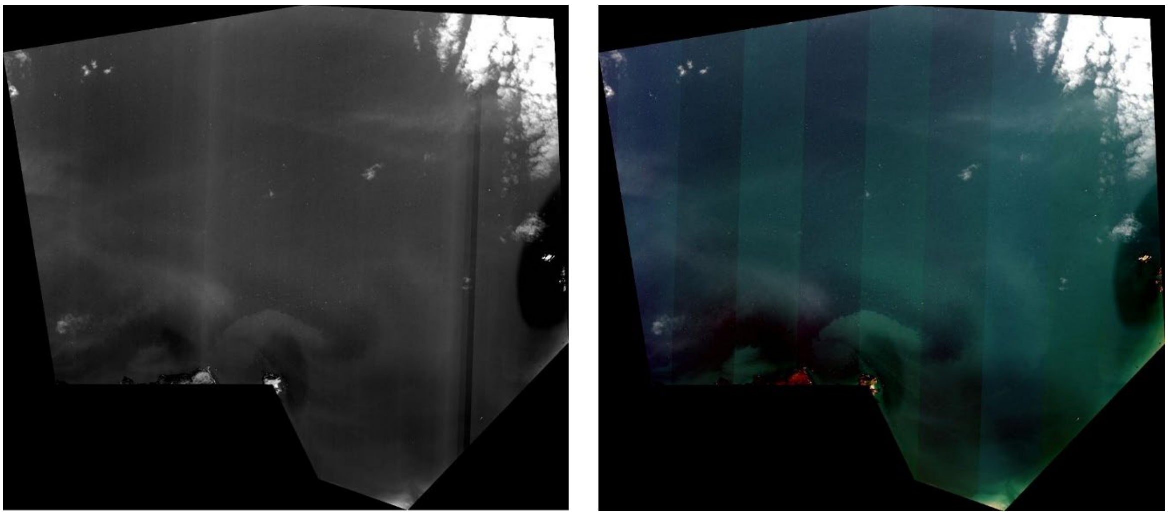

Figure 3: Left: Full resolution panchromatic image received from Maxar for St Ives Bay. Image ID: 104001006239FF00. Right: Full resolution multispectral imagery depicting St Ives Bay received from Maxar. Image ID: 104001006239FF00.

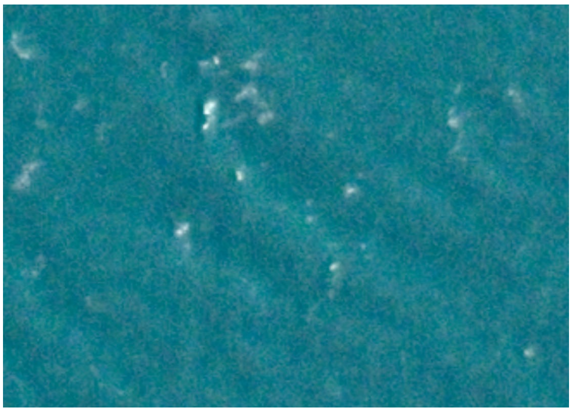

Figure 4: Example image from St Ives Bay tile R1C2 zoomed in to 1:1,500 scale. The wave pattern and some white caps are visible.

The scan identified four features that could be possible whales (Figure 5) as well as two boats and a possible cardinal buoy in image R2C2 (Figure 6). Expert opinion from H. Cubaynes was sought to verify these features, which concluded that none of these features could positively be identified as a large whale.

Figure 5: Possible whales identified in St Ives Bay image tile R1C1 (top) and R1C3 (bottom).

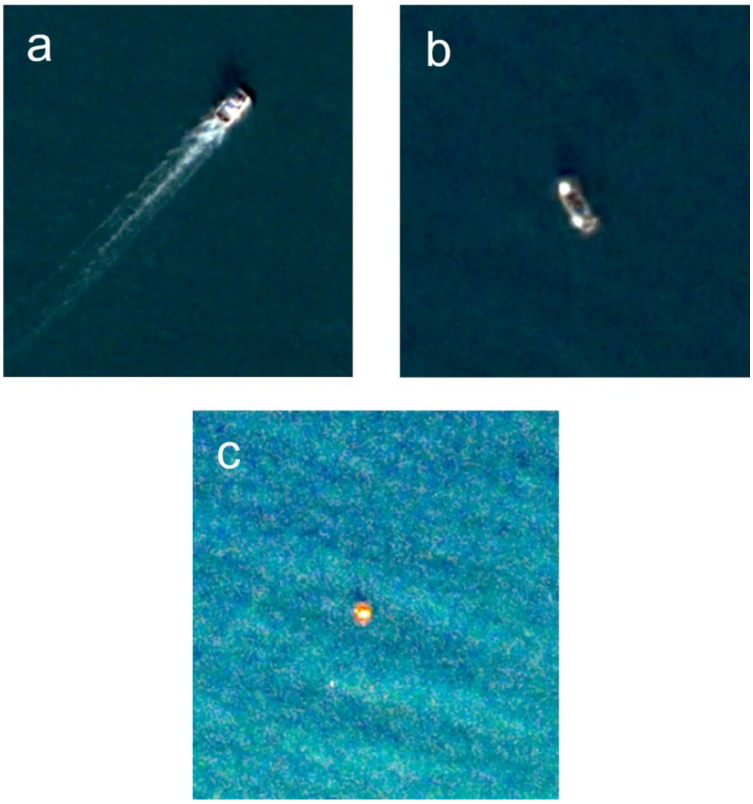

Figure 6: Vessels identified in St Ives Bay image tile R2C2 showing boats (a and b) and a marker buoy (c).

4.1.3 Botallack, manual scan results

One satellite image collected at 11:35 by the WorldView-3 satellite was available on 9 January 2021 at Botallack. The full image had 17% cloud cover; however, the area of interest (AOI) was free of cloud cover, but partially in cloud shadow (Figure 7).

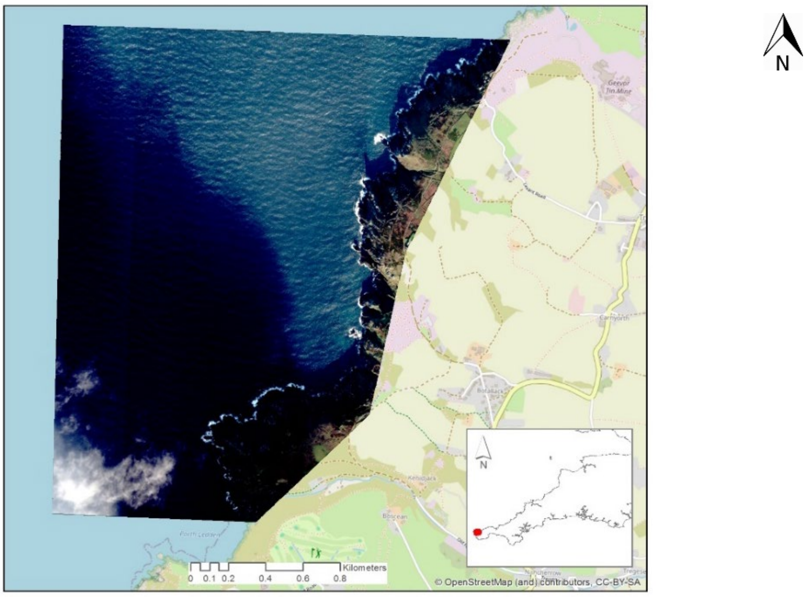

Figure 7: Preview satellite image taken from Maxar Technologies (2021) of Botallack in Cornwall taken the same day as a reported unknown large whale sighting, 9 January 2021. Image ID 10400100637E9F00. Basemap © Open Street Map.

The combination of a rough sea state and cloud shadow limit the possibility of identifying any potential features of interest in this image (Figure 8). No positive or possible whales were detected by the visual scan of the imagery of Botallack.

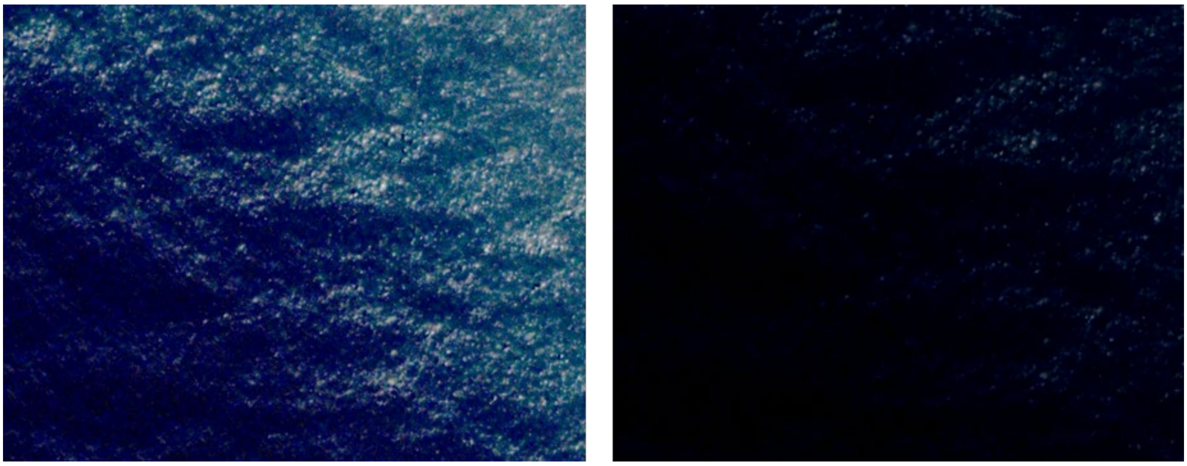

Figure 8: Examples of rough sea surface and colour-balancing options available in ArcMap.

4.2 Case study 2: Sei whales in the Falkland Islands

The Overseas Territory of the Falkland Islands has recorded at least 26 cetacean species, including seven species of baleen whale (Falklands Conservation 2020). Sei whales (*Balaenoptera borealis*) are the most frequently sighted species and can be regularly observed within shallow, coastal waters between December and May. Conversely to humpback whales in UK waters, sei whale field research has been conducted in the Falkland Islands since 2017 by Falklands Conservation. This work has consisted of air, land and sea surveys to assess abundance, distribution, behaviour and genetics, to inform management strategies, and to explore long-term monitoring approaches.

4.2.1 Sourcing Falkland Islands sei whale sightings data

Survey sightings reported on the Falkland Islands Whale Project social media page between June 2020 and March 2021 were reviewed. An additional search was performed for VHR imagery to coincide with a yacht-based survey carried out between 25 February 2018 and 1 April 2018 on the western coast of West Falkland (Weir *et al.* 2021). This study focussed on the shallow (less than 60 m depth) waters of King George Bay (KGB) and Queen Charlotte Bay (QCB) since these were highlighted as potential whale Key Biodiversity Areas (KBAs) by Taylor *et al.* (2016) (Figure 9).

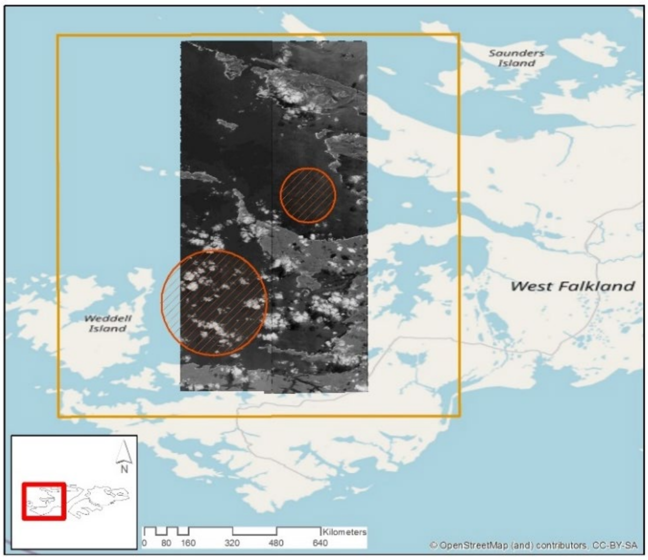

Figure 9: Study area extrapolated from Weir *et al.* (2021) represented in the orange box. King George Bay (KGB) and Queen Charlotte Bay (QCB) were highlighted in red as hatched areas represent potential whale Key Biodiversity Areas following Taylor *et al.* (2016). Satellite imagery available from 27 March 2018; Image ID: 104001003A029E00 and Image ID: 104001003B1A7500.

4.2.2 Manual scan results

The search on Maxar Discovery platform for imagery corresponding to the sightings in the Falkland Islands returned no matches. However, two overlapping images with moderate, patchy cloud cover, captured on 27 March 2018 at 14:12:32 (Image ID: 104001003A029E00) and 14:13:03 (Image ID: 104001003B1A7500), overlapped a portion of the area surveyed by Weir *et al.* (2021) between 25 February 2018 and 1 April 2018.

The manual scan of the Weir *et al.* (2021) survey area focussed on the KGB and QCB whale hotspots. The KGB hotspot comprised 12 tiles from rows 7 to 9 of the right-hand image found in the Maxar archive (ID 104001003B1A7500) (Figure 10).

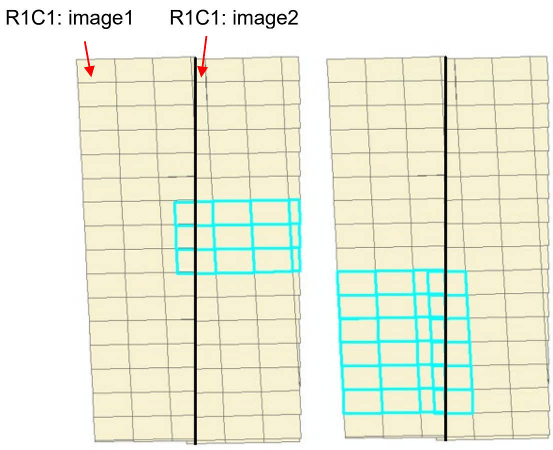

Figure 10: Tiled mosaic layout of the two Weir *et al.* (2021) survey area images from Maxar. The tiles covering the whale hotspot areas are depicted in blue for KGB (left) and QCB (right). The black line depicts the edge of the left-hand image (ID: 104001003A029E00) which overlaps the right-hand image (ID: 104001003B1A7500). Note that the column numbers relate to each image, that is, they restart for image 2 tiles.

The sea surface in the images, even after colour balancing was too rough for an effective manual scan in most tiles at 1:1,500 scale (Figures 11 and 12). A scan was performed on tiles R7C4, R8C1, R9C1 and R9C2, but no features of interest were identified.

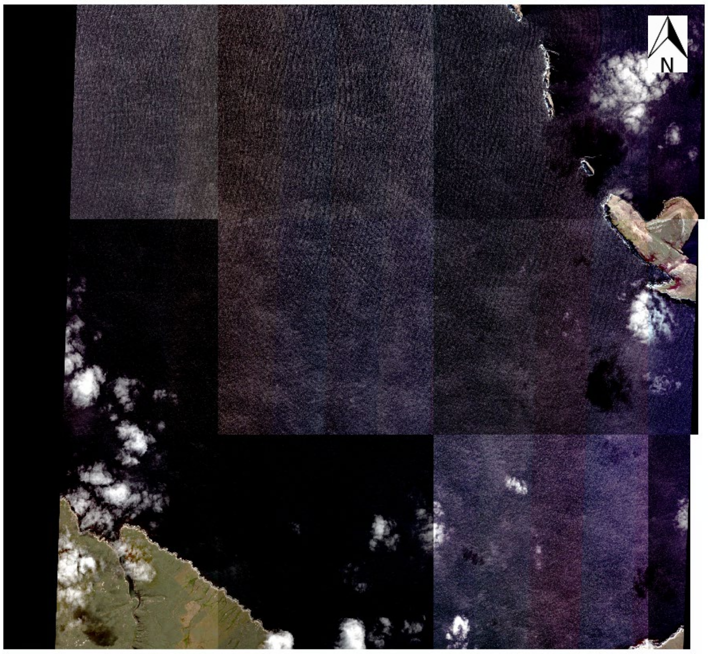

Figure 11: Tiled image .tif files for the KGB area of the Falklands Islands imagery. Image ID 104001003B1A7500.

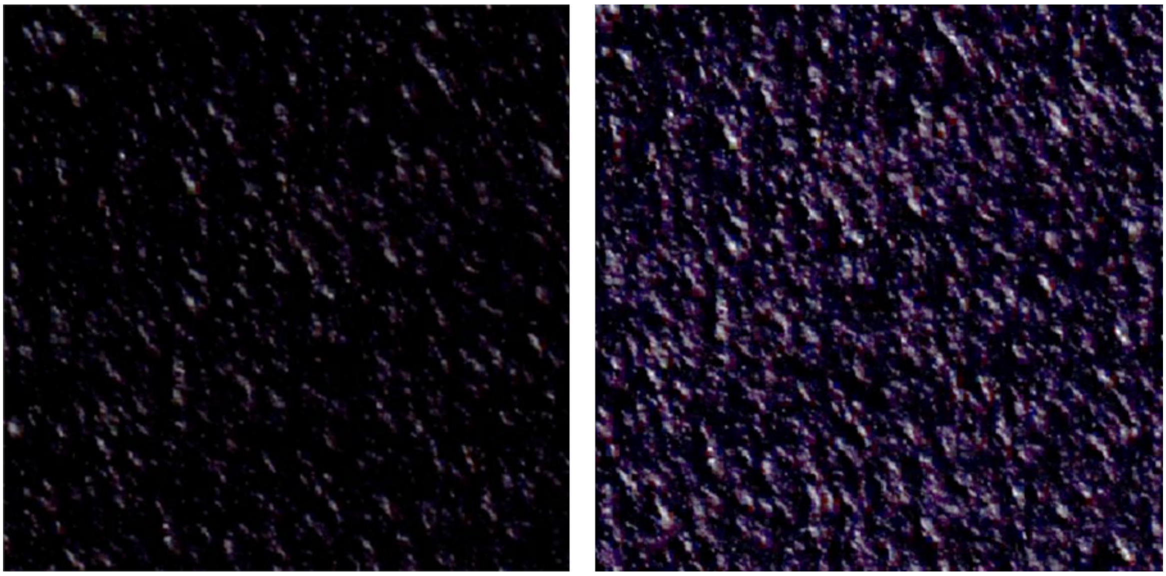

Figure 12: Sea surface in KGB when zoomed to 1:1,500 scale in image tile R9C4. The image on the left has had no colour balancing applied, whereas the image on the right has had a colour-balance technique applied, which has improved the contrast, but has increased the visible roughness of the sea surface.

The QCB hotspot comprised 23 tiles: rows 10 to 15 from image 1 and column 1 of rows 11 to 15 from image 2 (Figure 13). Besides the cloud cover, an initial scan of tile R10C1 proved these tiles to be too dark to effectively identify features of interest.

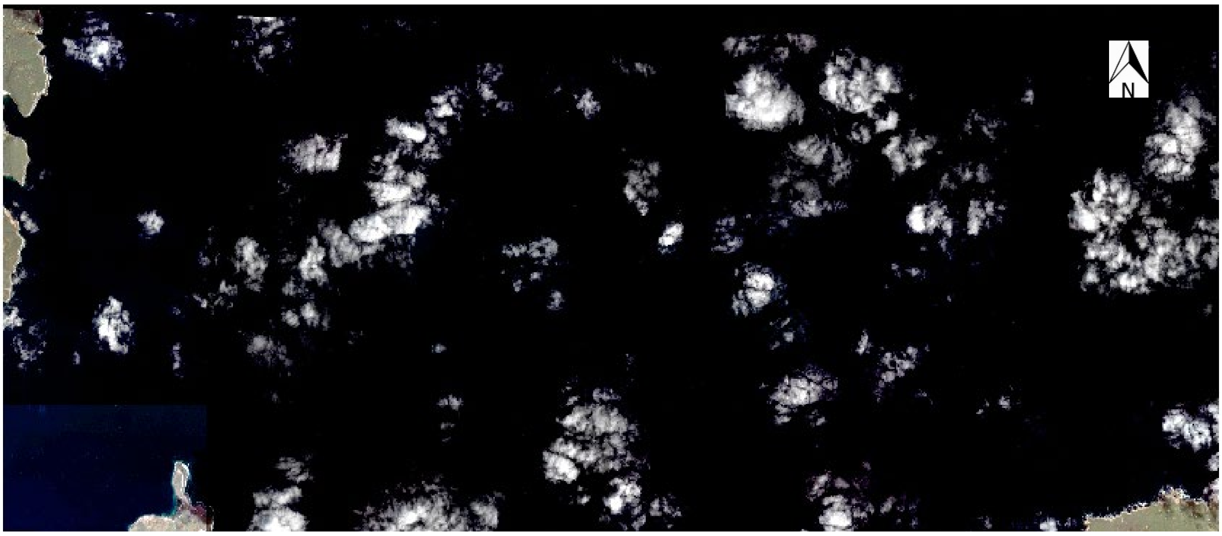

Figure 13: Tiled image .tif files for the QCB area of the Falklands Islands imagery.

4.3 Case study discussion

Of the 49 UK humpback sightings reviewed, only two were able to be matched in space and time to satellite imagery (Tables 6 and 7 in Appendix 2). These case studies highlight the present spatial and temporal coverage gaps in available archived satellite imagery. Similarly, in case study 2, there was no satellite imagery available to match any of the available sightings recorded and the imagery available for the survey area did not cover the whole site.

Much of the sightings' data used in these case studies did not provide specific location data such as latitude and longitude of observer, directional view, or estimated whale distance from the shore. It should be acknowledged that publicly available sightings' data are often shared at a reduced spatial resolution, or detail is withheld by the data custodian. The project time constraints limited the ability to formally request data from organisations, limiting searches to what was published online only. Where date-based matches between sightings and VHR images were possible, there were often mismatches between the time at which the satellite image was taken and the time of the sighting, making it possible that the animal may not be in its last sighted location at the time the image was taken. In some cases, imagery was available on dates close to the date of the sighting. It is possible that other satellite imagery providers, such as Planet and Airbus, may have imagery corresponding to the date and location for the sightings, which could be tested in a future study.

In case study 1, VHR satellite imagery of St Ives was of higher quality for detection conditions than for Botallack, with a calmer sea state and brighter image quality. Four possible whales were identified, although no confident detections were made. In contrast, images of Botallack were dark, with rough seas, making detection of features of interest challenging. In case study 2, cloud cover partially obscured a key area of interest assumed to have the highest whale density in the available Falklands Islands imagery (Figure 9). These images were also dark, and the application of colour-balancing to counteract the dark original imagers resulted in high contrast in a choppy sea, limiting the ability to detect any potential large whales. It is a known phenomenon that the appearance of the sea surface can change drastically between images taken only a few seconds apart due to the angle of the sensor relative to the sea surface and the amount of sunlight being reflected (Jackson & Alpers 2010).

The project has identified two key challenges that limit the present feasibility of utilising satellite imagery as part of large whale monitoring programmes:

1. Imagery acquired for both case study sites has highlighted the need for optimal weather conditions to achieve confident detections (cloud cover and sea state).
2. Suitable temporal and spatial coverage of areas of interest.

5 Recommendations

Investigations are needed into the minimum size of whale distinguishable (Fretwell *et al.* 2019; Clarke *et al.* 2021), and maximum depth of detection (Cubaynes 2019). Suggestions include the use of reflectance panels for calibration (Fretwell *et al.* 2014) or artificial whale models at various depths (Cubaynes *et al.* 2019).

More research and pilot studies are required to test the use of VHR satellite imagery across species, scenarios and locations; ideally comparing counts to data from traditional surveys, citizen science records and other validated observation data. The use of satellite imagery for monitoring the natural environment and wildlife is an active area of research, and rapid progress is being made. It is recommended that advancements are monitored, and that any pilot studies undertaken use the most up-to-date reliable approaches available, and with collaboration with other researchers/research initiatives within the field.

Further investigations into the effects of availability and perception bias and the development of methods to account for bias are required, as with traditional survey methods. Perception bias could be assessed through the use of multiple observers, but this would require lots of detections (Bamford *et al.* 2020). Estimating surfacing rate from video or overlapping images, and/or recording surface time, behaviour, sea state and turbidity may also help to more accurately account for whale surface availability (Bamford *et al.* 2020).

Assessment of, and accounting for, factors limiting detectability, such as weather conditions, would also be advantageous (Höschle *et al.* 2021). For instance, at 0.31 m spatial resolution in rough sea conditions, the size of "noisy" elements is likely to be within a single pixel (31 x 31 cm) making discrimination of whales feasible (Borowicz *et al.* 2019). Investigating the influence of environmental conditions on detectability could be further enabled through the use of remote sensed data such as environmental conditions (Clarke *et al.* 2021). Using imagery unaffected by weather, such as radar, offers one potential solution to issues with cloud cover, but as with optical imagery this would require higher resolution data (Höschle *et al.* 2021). Using sequences of images could also help to resolve uncertain detections, but these sequences of images captured over a short period of time are rarely available for remote offshore regions (Fretwell *et al.* 2014).

Ongoing discussion and collaboration between stakeholders and researchers is needed to establish the best approaches to data collection and analysis (Höschle *et al.* 2021). The release of freely available VHR imagery would also allow for the development of a global, open-source database that could be used to improve training for automated techniques (Clarke *et al.* 2021; Höschle *et al.* 2021). It is thought that the release of open water imagery would not compete with commercial activity since it is usually focussed on terrestrial or coastal areas (Guirado *et al.* 2019).

Automation or semi-automation of detections in VHR imagery is in its infancy and requires further research and development to address the challenges associated with the use of these data, discussed in this study. Object-based automation or rule-based analysis and deep learning techniques like CNN appear to show promise, and warrant further investigation and testing (Clarke *et al.* 2021; Rodofili *et al.* 2022). Additional data are required to achieve large training datasets needed for machine learning approaches. The use of aerial imagery for training has potential and sets of training imagery can be artificially increasing through augmenting the images. Opening access to annotated VHR imagery as a shared resource would enable more rapid development of these techniques (Clarke *et al.* 2021; Höschle *et al.* 2021; Rodofili *et al.* 2022). Other developments for automation include establishing an appropriate analysis (coding) framework and pre-processing workflows for a standardised approach (Höschle *et al.* 2021; Cubaynes *et al.* 2023).

The computational and storage demands required for VHR image analysis pose a challenge for most users of these kinds of data. Making use of online data solutions and multi-institutional collaborations would be important to share knowledge and resources for effective use of these data (Clarke *et al.* 2021).

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Appendix 1: Studies included in the literature review

Table 5: Author, year, title, and summary of the 24 papers reviewed in full for this literature review. The papers are presented in chronological order (oldest first). The papers identified through a review of references are denoted by an asterisk.

Citation	Title	Summary	Satellite and image resolution
Abileah, (2001)	Use of high-resolution space imagery to monitor the abundance, distribution, and migration patterns of marine mammal populations	An initial assessment of the detectability of marine mammals. A signal to noise ratio model found that a simulated 14 m elliptical target can be detected up to a depth of 24 m, thus demonstrating the detectability of large marine mammals.	Ikonos; 1 m panchromatic and 4 m multispectral
Abileah, (2002) *	Marine mammal census using space satellite imagery	First images of whales from space – a captive orca (*Orcinus orca*), and possible humpback whales (*Megaptera novaeangliae*) in Hawaii. However, the 1 m/4 m panchromatic/multispectral spatial resolution provided by IKONOS-2 was not sufficient to make confident identifications.	Ikonos-2; 0.82 m panchromatic and 4 m multispectral
Platonov *et al.* (2013)	The possibility of using high resolution satellite images for detection of marine mammals	Visual wave pattern analysis of GeoEye-1 0.5 m panchromatic image illustrated that beluga whales (*Delphinapterus leucas*) can be detected in sufficiently clear surface waters and that a bowhead whale (*Balaena mysticetus*) could be identified in the absence of ripples by the contrast of the blow with the darker ocean surface.	GeoEye-1; 0.5 m panchromatic
Fretwell *et al.* (2014)	Whales from space: counting southern right whales by satellite	First study to use satellite imagery to count baleen whales. Methods included a comparison of automated detection techniques, with thresholding achieving the best results. The study highlights the usefulness of the coastal band, which can see deeper into the water column.	WorldView-2; 0.46 m panchromatic and multispectral (~2 m)

Citation	Title	Summary	Satellite and image resolution
Leaper & Fretwell, (2015) *	Results of a pilot study on the use of satellite imagery to detect blue whales off the south coast of Sri Lanka	Pilot study for blue whale (*Balaenoptera musculus*) detection using WorldView-2 satellite images concurrent with boat survey period in an area of dense shipping and whales. The study was unable to classify the nine targets with any degree of confidence due to confusion with waves.	WorldView-2
Thums *et al.* (2018) *	Humpback whale use of the Kimberley; understanding and monitoring spatial distribution	A comparison of archive WorldView-2 and tasked WorldView-3 imagery for humpback whale detection, showing imagery. This study suggests the imagery from WorldView-2 lacks the detail for clear shape distinction, compared to the higher resolution of WorldView-3.	WorldView-2 and WorldView-3; 1.24 m multispectral and 0.31 m panchromatic
Vukelic *et al.* (2018)	A cetacean monitoring system that integrates citizen science and satellite imagery	Presentation of a model for real-time monitoring of cetaceans by combining citizen science and satellite image processing.	N/A
Cubaynes *et al.* (2019)	Whales from space: four mysticete species described using new VHR satellite imagery	First use of WorldView-3 imagery for detecting large whales using a visual and spectral analysis of four baleen whale species. The study concluded that fin (*Balaenoptera physalus*) and gray whales (*Eschrichtius robustus*) are easier to distinguish from surrounding water than humpback and southern right whales (*Eubalaena australis*) due to contrasting body colour and prone body position.	WorldView-3

Citation	Title	Summary	Satellite and image resolution
Borowicz *et al.* (2019)	Aerial-trained deep learning networks for surveying cetaceans from satellite imagery	Pilot study as part of the SPACEWHALE project, in which a semi-automated pipeline for whale detection from VHR satellite imagery using convolutional neural networks (CNNs), is trained on aerial imagery, and tested on WorldView-3 imagery. The study aimed to detect all images with a high probability of being whale to minimise labour required for expert annotation. The best model correctly classified all image grid-squares containing whales, and 94% of those containing water.	WorldView-3
Guirado *et al.* (2019) *	Whale counting in satellite and aerial images with deep learning	This study proposes a large-scale, generalisable two-step whale counting method. An initial CNN classifies whale presence/absence, then a second CNN locates and counts each whale. The networks were trained on a combination of freely available satellite and aerial imagery and tested on freely available Google Earth imagery for 10 whale hotspots. Whales were detected when aggregated at breeding grounds, but not across migratory routes or feeding grounds.	Google Earth imagery, consisting of USGS aerial, WorldView-3, QuickBird-2, GeoEye-1, SPOT-6 and WorldView-2. A variety of panchromatic and multispectral imagery, ranging from 0.31 m to 1.84 m
Fretwell *et al.* (2019)	Using remote sensing to detect whale strandings in remote areas: the case of the sei whales mass mortality in Chilean Patagonia	A combination of manual and automated methods was applied to WorldView-2 (0.5 m) satellite imagery to identify and count sei whales from a discrete stranding event. Stranded whales were easily detected by visual analysis, but spectral indices were unsuitable for automation due to the variation in colour during the decomposition process.	WorldView-2

Citation	Title	Summary	Satellite and image resolution
Bamford *et al.* (2020)	A comparison of baleen whale density estimates derived from overlapping satellite imagery and shipborne survey	First comparison of counts from WorldView-3 satellite imagery and a ship-based survey. Estimates based on satellite imagery were considerably lower than those from the ship-based survey, but when adjusted for surface availability and weather conditions, fell within an order of magnitude of the ship-based estimates.	WorldView-3
Cubaynes *et al.* (2020)	Spectral reflectance of whale skin above the sea surface: A proposed measurement protocol	Tested whether spectral reflectance of live whales could be ascertained from dead whale tissue to inform the development of tools for differentiating species and measuring at what depths whales are detectable. The study did not recommend their approach due to darkening of the samples after death. The authors suggested ways in which spectral reflectance could be captured directly from live whales using small aircraft over whales in the ocean, or from live stranded whales.	WorldView-3
Corrêa *et al.* (2021)	Use of satellite imagery to identify southern right whales (Eubalaena australis) on a Southwest Atlantic Ocean breeding ground	Pleiades-1A VHR satellite imagery, accessed via Google Earth preformed best for detecting whales, when compared with Sentinel 2, Landsat 8, Rapid Eye, and Planet Scope satellite imagery. The results from satellite image were comparable to in-situ aerial surveys of a southern right whale breeding ground.	Google Earth; Pleiades-1A (multispectral, 0.5 m), Sentinel 2, Landsat 8, Rapid Eye (multispectral, 5 m), and Planet Scope (multispectral, 3 m)

Citation	Title	Summary	Satellite and image resolution
Höschle *et al*. (2021)	The potential of satellite imagery for surveying whales	A review in which the future application of VHR satellite imagery to urgent questions in whale conservation is discussed. The challenges in automating detection and extending the use of the technology are also highlighted. The authors conclude that future research will require collaboration between disciplines to overcome these challenges and to achieve basin-scale marine surveys, which are not possible using traditional methods.	N/A
Charry *et al.* (2021)	Mapping Arctic cetaceans from space: A case study for beluga and narwhal	A study to review the ability of VHR satellite imagery for observations of small tooth cetaceans; narwhal (*Monodon monoceros*) and beluga, in Artic waters using manual scanning with multiple observers. This is the first example of differentiating between two similar sized cetacean species. The there was 100% agreement between observers when the animals were at the surface, and disagreement when the animals were submerged or confused with other features.	WorldView-3
Clarke *et al.* (2021)	Cetacean Strandings from Space: Challenges and Opportunities of Very High Resolution Satellites for the Remote Monitoring of Cetacean Mass Strandings	A review of the current data gaps in global strandings monitoring, including the opportunities and challenges in using VHR satellite imagery to monitor strandings events and detailing the next steps for the field.	N/A
Cubaynes & Fretwell (2022)	Whales from space dataset, an annotated satellite image dataset of whales for training machine learning models	A dataset of 633 annotated whale objects covering four species gathered from VHR satellite images from multiple satellites as a resource for training and testing automatic detection systems.	WorldView-3, WorldView-2, GeoEye-1 and Quickbird-2

Citation	Title	Summary	Satellite and image resolution
Höschle *et al.* (2022)	Satellite surveys prove a reliable monitoring method for high latitude southern right whale habitat	Comparing counts of southern right whale from the SPACEWHALE detection algorithm (trained using aerial images of minke whales (*Balaenoptera acutorostrata*)) on satellite imagery of 0.5 m resolution, against vessel based survey observations. Each method found a comparable number of whales, with vessel surveys recording a higher number of calves which may not have been visible in the VHR imagery due to relative position to the mother whale.	WorldView-2
Rodofili, *et al.* (2022)	Remote sensing techniques for automated marine mammals detection: A review of methods and current challenges	A review of methods to automate the detection of marine mammals in VHR satellite and unmanned aerial vehicles (UAV) imagery. CNN methods show promise but need continued research and development for accurate automation of counts, and user review is currently recommended.	Various
Ramos *et al.* (2022)	Lord of the Rings: Mud ring feeding by bottlenose dolphin in a Caribbean estuary revealed from sea, air and space	Report of mud ringing feeding behaviour observed in a bottlenose dolphin (*Tursiops truncatus*) population. This is the first use of satellite imagery to observe feeding behaviour of small cetaceans	Google Earth; WorldView-2
Cubaynes *et al.* (2023)	Annotating very high-resolution satellite imagery: A whale case study	Proposal for a standardised workflow for the annotation of VHR satellite imagery for cetacean species, using ESRI ArcMap and ARCPro.	N/A

Citation	Title	Summary	Satellite and image resolution
Hodul *et al.* (2023)	Individual North Atlantic right whales identified from space	Demonstration of the detection and identification of individual North Atlantic right whales (*Eubalaena glacialis*) using VHR (15 cm) satellite imagery. This is the first use of sub 30 cm resolution imagery for marine mammal observations, the imagery was tasked using WorldView-3 and to the spatial resolution enhanced by Maxar using a proprietary algorithm.	WorldView-3
Khan *et al.* (2023)	A Biologist's Guide to the Galaxy: Leveraging Artificial Intelligence and Very High-Resolution Satellite Imagery to Monitor Marine Mammals from Space	A description of and lessons learned from a collaborative cross-sector initiative; Geospatial Artificial Intelligence for Animals (GAIA) initiative, to enable to use of satellite imagery for monitoring two cetacean species; North Atlantic right whale and beluga whale. GAIA uses both archive imagery and satellite tasking.	WorldView-3, WorldView-2, and GeoEye-1

Appendix 2: Humpback whale sightings

Table 6: 2021 sightings taken from the Scottish UK Humpback Catalogue (Scottish UK Humpback Catalogue, 2021) and results of search for corresponding satellite imagery at discover.digitalglobe.com.

Sighting	Imagery available	Notes – dates when imagery is available
22 December 2020 (1) Firth of Forth.	No	25 Nov 2020 or 22 Feb 2021
24 December (1) Isles of Scilly.	No	21 Oct 2020 or 24 Mar 2021
17 January (2) Firth of Forth.	No	25 Nov 2020 or 22 Feb 2021
18 January (2) Tain, Moray.	No	12 Sept 2020 or 12 Feb 2021
18 January (2) Helmsdale.	No	19 Feb 2021
24 January (1) Firth of Forth.	No	25 Nov 2020 or 22 Feb 2021
25 January (1) NW of Orkney.	No	12 Sept 2020 or 28 Mar 2021
January 30 (2) Firth of Forth.	No	25 Nov 2020 or 22 Feb 2021
February 9th Fishermen report 2 humpbacks at port seton.	2 days out of sync with sighting.	11 Feb 2021
1 humpback 23/2/21 at 4pm fairway buoy, fishermen's report.	No	Apr 2020 or 8 Mar 2021
1 humpback seen passing Kinghorn heading east and last sighting Methil 28/2/21.	No	11 Feb 2021 or 13 Mar 2021
31 January (1) Pentland Firth.	No	latest July 2020
31 January (2) Northumberland.	No	latest May 2020
1 humpback seen at Barns Ness lighthouse Dunbar on 2/3/21.	No	No imagery since 2019
1 humpback seen at wind farm just outside the Forth 2/3/21. Different individual to Barns Ness sighting.	No	No imagery since 2019
3 humpbacks seen Tiumpan head 4/3/21.	No	latest May 2020
Deceased humpback calf Tolsta 5/3/21.	No	latest May 2020
Deceased humpback whale Dunstanburgh 5/3/21.	No	

Sighting	Imagery available	Notes – dates when imagery is available
Washed up at Blyth and can confirm by fluke ID this humpback is the same animal that was identified as arriving on Northumberland coastline on 31st January.	No	latest Nov 2020
Deceased humpback Falmouth 12th March.	No	latest Dec 2020

Table 7: 2021 sightings in South-west England and south Wales taken from the Sea Watch Foundation recent listings online tool (Sea Watch Foundation, 2021)and results of search for corresponding satellite imagery at discover.digitalglobe.com.

Sighting	Imagery available	Notes – dates when imagery is available
Fin whale (x1) – Peninnis Head, Isle of Scilly, Cornwall at 10:25 on 9 Mar 2021 by Angie, Mark Underwood	No	7 Jan and 24 Mar
Fin whale (x2) – Peninnis Head, Isle of Scilly, Cornwall at 07:50 on 8 Mar 2021 by Angie, Mark Underwood	No	7 Jan and 24 Mar
Fin whale (x1) – Peninnis Head, Isle of Scilly, Cornwall at 08:00 on 5 Mar 2021 by Angie, Mark Underwood	No	7 Jan and 24 Mar
Fin whale (x1) – Peninnis Head, Isle of Scilly, Cornwall at 08:00 on 5 Mar 2021 by Angie, Mark Underwood	No	7 Jan and 24 Mar
Humpback whale (x1) – Old Town, Isle of Scilly, Cornwall at 15:30 on 27 Feb 2021 by Angie, Mark Underwood	No	7 Jan and 24 Mar
Large whale (x1) – Halldrine cove, Cornwall at 13:00 on 27 Feb 2021 by Clare Murphy	No	9 Jan or 8 Mar
Humpback whale (x1) – East Pier, Somerset at 12:45 on 11 Feb 2021 by Luke Goodley	No	Latest Nov 2020
Fin whale (x1) – SW of the Isles of Scilly at 09:00 on 25 Jan 2021 by John Peacock	No	Oct or Mar
Cetacean species (x3) – Pendennis Point, Cornwall at 16:05 on 24 Jan 2021 by Katie Bliss	No	latest Dec 2020

Sighting	Imagery available	Notes – dates when imagery is available
Humpback whale (x1) – St Mary’s Roads, Isles of Scilly at 16:00 on 16 Jan 2021 by John Peacock	No	Oct or Mar
Large whale (x0) – Botallack Crown Mines, West Cornwall at 16:00 on 9 Jan 2021 by Gail Charman	Yes	WV3 ID: 10400100637E9F00, clouds 17% - area looks half in shadow
Humpback whale (x3) – Cape Cornwall NCI, Cornwall at 11:00 on 6 Jan 2021 by Sarah Bell	No	Latest June 2020
Humpback whale (x1) – Between St Mary’s and Samson, Isles of Scilly at 12:00 on 4 Jan 2021 by John Peacock	No	Oct or Mar
Humpback whale (x1) - Gwynver beach, Cornwall at 15:00 on 3 Jan 2021 by Rob Pittam	No	Latest June 2020
Humpback whale (x1) – Off St Mary's, Isles of Scilly at 14:00 on 2 Jan 2021 by John Peacock	No	Oct or Mar
Humpback whale (x2) – The Roads, Isles of Scilly on 2 Jan 2021 by Robert Lambert	No	Oct or Mar
Fin whale (x2) – Off St Mary's, Isles of Scilly at 12:00 on 1 Jan 2021 by John Peacock	No	Oct or Mar
Humpback whale (x1) – St Mary's, Isles of Scilly at 11:30 on 1 Jan 2021 by John Peacock	No	Oct or Mar
Fin whale (x2) – St Mary’s, Isles of Scilly at 11:00 on 1 Jan 2021 by Charles Crawford	No	Oct or Mar
Fin whale (x2) – Peninnis Head, St Mary’s, Isles of Scilly on 1 Jan 2021 by Robert Lambert	No	7 Jan
Humpback whale (x1) – Between St Mary’s (Garrison) and Samson, Isles of Scilly at 14:00 on 26 Dec 2020 by Charles Crawford	No	Oct or Mar

Sighting	Imagery available	Notes – dates when imagery is available
Humpback whale (x1) – Between St. Mary's and St. Agnes, Isles of Scilly at 15:00 on 25 Dec 2020 by Charles Crawford	No	Oct or Mar
Humpback whale (x1) – Pordenack point, Cornwall at 16:10 on 24 Dec 2020 by Joseph Gray	No	Latest June 2020
Humpback whale (x1) – Between the Isles of Scilly, Cornwall at 16:00 on 24 Dec 2020 by John Peacock	No	Oct or Jan
Humpback whale (x1) – The Roads, Isles of Scilly at 15:30 on 24 Dec 2020 by Robert Lambert	No	Oct or Mar
Fin whale (x1) – St Ives, Cornwall on 20 Dec 2020 by Cornwall Wildlife Trust Sea Quest South West	1 week out of sync with sighting.	7 or 27 Dec
Humpback whale (x2) – St Ives Bay, Cornwall at 14:00 on 7 Dec 2020 by David Perry	Yes	ID: 104001006239FF00, WV3, 41% cloud but bay looks clear in preview; neighbouring image 10400100632A0B00 has slice of bay at side too
Humpback whale (x1) – Lamorna, Cornwall at 15:15 on 2 Dec 2020 by Michael Amos	No	Jun 2020 or Mar 2021
Minke whale (x1) – Logan Rock, Cornwall at 13:50 on 2 Dec 2020 by Michael Amos	No	Jun 2020 or Mar 2021

Appendix 3: Google Earth VHR satellite imagery

Table 8: Table adapted from Guirado *et al.* (2019) and amended. Location and details of the ten whale hotspot areas evaluated together with the acquisition date and season of the satellite images in Google Earth. For each image source in Google Earth (reduced spectral resolution) these metadata are provided: the satellite (GE-01: GeoEye-01; QB-02: QuickBird-2; SPOT-6; USGS: United States Geological Survey orthoimage; WV-02: WorldView-2; and WV-03: WorldView-3), the pixel size at nadir in metres (m), and the sensor spectral resolution (M = Multispectral; P = Panchromatic).

Site IDs Site names (country)	Latitude Longitude WGS84	Whale watching period	Date of Google Earth image	Season of acquisition date	Image source Pixel size (m)	Whales detected?
1. Hawaiian Islands (USA)	20.636602, −156.462511	December to-April	3 April 2013 13 January 2013	Breeding	USGS aerial 0.15 M	Y
2. Baja California (Mexico)	26.769961, −113.242382	February	20 February 2017	Breeding	WV-03 0.31 P 1.24 M	Y
3. Valdés Peninsula (Argentina)	−42.603384, −64.810850	May to December	18 September 2003	Breeding	QB-02 0.61 P 2.5 M	Y
4. Witsand (South Africa)	−34.390203, 20.879985	July to October	9 August 2009	Breeding	GE-01 0.46 P 1.84 M	Y
5. Memba (Mozambique)	−14.185282, 40.691405	June to July	23 June 2017	Breeding	SPOT-6 1.5 P 6.0 M	Resolution too low to make confident detections
6. Coral Sea (Australia)	−24.622170, 153.291559	September to - November	13 September 2005	Breeding	QB-02 0.61 P 2.5 M	Y

Site IDs Site names (country)	Latitude Longitude WGS84	Whale watching period	Date of Google Earth image	Season of acquisition date	Image source Pixel size (m)	Whales detected?
7. Enderby Island (New Zealand)	−50.501698, 166.282294	July to September	2 September 2012	Breeding	WV-02 0.46 P 1.84 M	Y
8. Peruvian coast (Peru)	−14.253483, −76.159243	June to September	9 March 2016	Migrating/Feeding	WV-03 0.3 P 1.24 M	N
9. Canary Islands (Spain)	28.139039, −16.796631	August to November	10 March 2017	Migrating	WV-02 0.46 P 1.84 M	N
10. Japanese coast (Japan)	41.947425, 143.246413	April	5 October 2014	Migrating	WV-02 0.46 P 1.84 M	N