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ABSTRACT

The application of Very-High-Resolution (VHR) satellites to survey cetaceans has gained considerable traction over the last decade. Large whale species in particular lend themselves to detection by VHR imagery of ~0.50m resolution or less. Processing of satellite images can be manually intensive, and consequently artificial intelligence methods are underpinning progress in this field. We have developed a method that uses a Faster-R-CNN (Region-based Convolutional Neural Network) object detection algorithm to process VHR imagery. This has been coupled with a manual species identification stage and packaged as the SPACEWHALE service. The service was used to acquire and process WorldView-2 archival images (~0.50 m resolution) of Port Ross, Auckland Island - Maukahuka in August 2020 to investigate the detection of southern right whales during the austral winter on this well-known breeding ground. The period of image acquisition coincided with boat-based surveys of the area which were used to compare the effectiveness of SPACEWHALE. The number of whales detected by both methods were equivalent, despite the 12-hour difference between the timing of data collection. The number of calves detected by satellite was slightly lower than the boat-based surveys, likely due to the algorithm missing calves that were completely obscured by their mothers during the snapshot survey. Use of higher resolution images (~0.30 m) may improve detection of calves that are not entirely hidden by their mothers. The SPACEWHALE survey did provide additional coverage and possible whale detections in a secondary area that has received little on-the-water survey effort; whilst this area is more exposed than Port Ross and is likely less suitable habitat, as the population continues to grow, areas beyond Port Ross may warrant research effort to determine whether this is a potential extension of core habitat or serves some other biological function for the whales (e.g., foraging). Satellite surveys are an effective alternative to monitor large whales in remote areas and can be used to augment existing data and to help explore and fill data gaps.

Key Words: Satellite-based monitoring, Southern Right whales, remote areas, high latitudes

INTRODUCTION

Over the last decade, the use of Very High Resolution (VHR) satellites to survey cetaceans has gained considerable traction. The first study proving that it was possible to count whales from satellite images successfully surveyed southern right whales (*Eubalaena australis*) breeding in part of the Golfo Nuevo, Península Valdés in Argentina (FRETWELL et al. 2014). The method has since been used to monitor this species on breeding grounds off Brazil (CORRÊA et al. 2022) and has been applied to other large whale species including humpback (*Megaptera novaeangliae*), fin (*Balaenoptera acutorostrata*), and gray whales (*Eschrichtius robustus*) (CUBAYNES et al. 2019; BAMFORD et al. 2020). Charry et al. (2021) successfully detected medium sized whales, namely beluga (*Delphinapterus leucas*) and narwhal (*Monodon monoceros*), using VHR imagery, taking advantage of the high contrast between these smaller species and the sea surface to facilitate their detection. The method is also useful for monitoring cetacean stranding events (CLARKE et al. 2021) through archival imagery. It has also successfully been used to identify a specific ecotype of the common bottlenose dolphins (*Tursiops truncatus*) in the interior of Florida Bay that hunts fish by encircling their prey with mud rings which are visible in VHR imagery (RAMOS et al. 2022).

The use of "satellite surveys" is not without challenges; the greatest being the need for relatively cloud free and calm survey conditions. However, traditional monitoring methods including from ship and aircraft suffer similar limitations in addition to being largely constrained to accessible survey areas. The use of satellites presents an opportunity for data collection in remote and inaccessible regions that have received little or no survey effort from traditional platforms. Satellites can also capture relatively large areas in a short space of time, providing a "snapshot" of surfacing or near surface whales. To date, published satellite studies have predominately relied upon manual processing of the imagery which is time consuming (CUBAYNES et al. 2019; BAMFORD et al. 2020; CHARRY et al. 2021; CLARKE et al. 2021). Speeding up image processing using automated deep-learning algorithms was the logical next step in the development of this methodology (HÖSCHLE et al. 2021). GUIRADO et al. (2019) used Convolutional Neural Networks (CNN) to find whales in satellite and aerial images of open data sources. We used the CNN to build an "object detection algorithm" (BOROWICZ et al. 2019) but have since improved upon this and incorporated an algorithm that uses a two-stage "Faster R-CNN network" (REN et al. 2015) into the semi-automated "SPACEWHALE[1]" satellite survey service that is verified manually by a large review team.

Using SPACEWHALE, we investigated the utility of this satellite-based platform for a case study examining southern right whale (tohorā) abundance and distribution in Port Ross, a harbour in the north-east part of the Auckland Islands – Maukahuka (hereafter Auckland Islands), in the Aotearoa New Zealand (hereafter New Zealand) sub-Antarctic. Concentrations of southern right whales at Port Ross were first surveyed in the 1990s (PATENAUDE et al. 1998; PATENAUDE & BAKER 2001) and this area is the primary calving ground in New Zealand's waters during the Austral winter (PATENAUDE 2000; STEWART & TODD 2001; CARROLL et al. 2011, 2013, 2014). The New Zealand sub-Antarctic population was estimated to number approximately 2000 whales in 2009, and growing at a rate of 7% (95% CI: 5-9%) based on genotype mark recapture (CARROLL et al. 2013). CHILDERHOUSE & DUNSHEA (2008) reported that over 200 southern right whales can occur in Port Ross in a single day. Therefore, this location represented a good testing ground for the practical use of the SPACEWHALE technology and a trial was planned. Additionally, information from boat-based surveys in Port Ross during the period provide context for assessing the effectiveness of SPACEWHALE to detect southern right whales.

MATERIAL AND METHODS

Satellite survey

The WorldView-3 satellite, operated by MAXAR and launched in 2014, offers the only commercially available VHR panchromatic images with an on-the ground pixel size of ~0.31 m; this improved upon WorldView-2 satellite imagery of ~0.50 m resolution. We scheduled satellite passes for the WorldView-3 sensor for a core period from 12 July 2021 – 30 August 2021 for an area that covered 1000 km² of Port Ross and adjacent waters; the timing was coincident with boat and drone surveys being undertaken. In total, 10 satellite overflights were planned during this time but only six were achieved due to the satellite being unavailable as the operator had higher priority tasks. However, on all six overflights, the images were obscured with 98-100% cloud cover. Therefore, an alternative solution to deliver a satellite survey of this area was sought.

We redefined an area of just 100 km² (Figure 1) to cover the area around Port Ross, an area sheltered from the prevailing westerly winds. We then investigated whether the SPACEWHALE algorithm would successfully detect whales from the WorldView-2 archived images which are of poorer resolution (~0.50 m). Two suitable images were obtained from passes over the area but for August in the previous year:

Pass 1: 17.08.2020 10:28:05 New Zealand time

Pass 2: 25.08.2020 10:32:25 New Zealand time

These passes did not overlap exactly in time with the boat-based surveys but data were collated for the 16th August 2020 (see Small boat based surveys) to provide a valuable comparison of detections and distribution from two sampling methods approximately 12 hours apart.

[1] https://www.spacewhales.de/

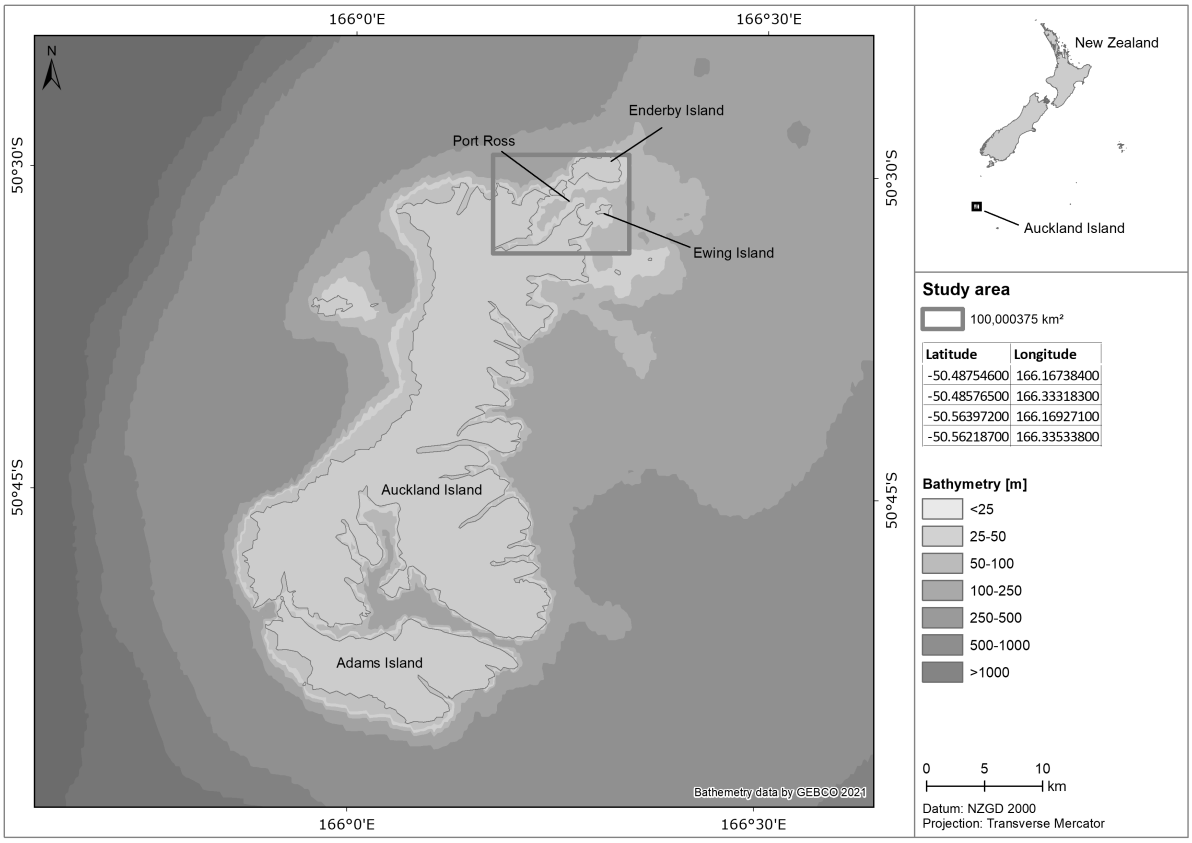

Figure 1 SPACEWHALE study area of Port Ross (100 km²), Auckland Islands, New Zealand.

SPACEWHALE processing

The SPACEWHALE detection algorithm is trained using down-sampled aerial images of minke whales (*Balaenoptera acutorostrata*) from aircraft-based surveys that used high-resolution digital video during 2012 to 2019 in the UK and Germany. The general dimensions of a minke whales' body approximates that of other whales and it was assumed that they could be used for object detection, particularly with data augmentation techniques available to us. In addition, down-sampled drone footage from blue (*Balaenoptera musculus*) and humpback whales improved the accuracy of our algorithm in detecting different whale species. The digital aerial images, with an original resolution of ~2 cm, were down-sampled to 0.46m to match the resolution of the WorldView-2 satellite imagery obtained for this study. Additional whale images detected in WorldView-2 and WorldView-3 were also used to train the algorithm.

To process and prepare the imagery for automated and manual detection and review, the lower resolution multi-spectral bands were pansharpened with the higher resolution panchromatic bands to obtain the VHR multi spectral imagery. For the whale detection processing, the satellite images were converted to PNGs, which is a smaller data format than GeoTiff and thus better for improving computational efficiency for computer vision. These images were then split into 800 x 800-pixel clips and used by the SPACEWHALE algorithm to detect objects. All detected objects were georeferenced, collated and passed to an expert large internal review team to identify to the lowest taxonomic level, with the results tabulated for final assessment. Identifications were classified as "definite", "likely" and "possible":

1. Definite - very clear whale features such as phenotype, fluke, callosities, and according to the size and position of the animal to be an adult or juvenile animal

2. Likely – most of the features (e.g. object shape and dimensions) are whale like

3. Possible – a few features are whale like but may be mistaken with other objects

Small boat-based surveys

Small boat surveys were conducted to collect photo-identification data and skin biopsy samples, and deploy satellite tags on southern right whales in Port Ross during August 2020 (CARROLL et al. In Review, ForInfo SC/68D/ForInfo/25), following previous published methodology (CARROLL et al. 2013). Two small research

platforms (3-5 m rigid-hulled inflatable boats) operated in Port Ross and slowly approached groups of southern right whales. If the whales did not show avoidance behaviour, the boats closely approached for photo-ID and skin biopsy sample collection. Whale positions were recorded with a handheld GPS, and the boats spent a combined total of 11 hours 44 minutes on the water on 16 August 2020.

RESULTS

A summary of southern right whale detections is given in Table 1. At least 120 southern right whales (definite adults and calves) were detected in the single pass on 17th August 2020; this increases to 171 animals with the inclusion of likely whales. The definite detections could be considered minimum counts as currently, they are not corrected for whales submerged at the time of the surveys. On the 17th August, 57% and 24% of whale detections were classified as being definite and likely, respectively. On the 25th August, of the 108 detections the majority (82%) were only possible whales.

Whales were detected in different postures including swimming on their side, emerging on the water surface and nursing (

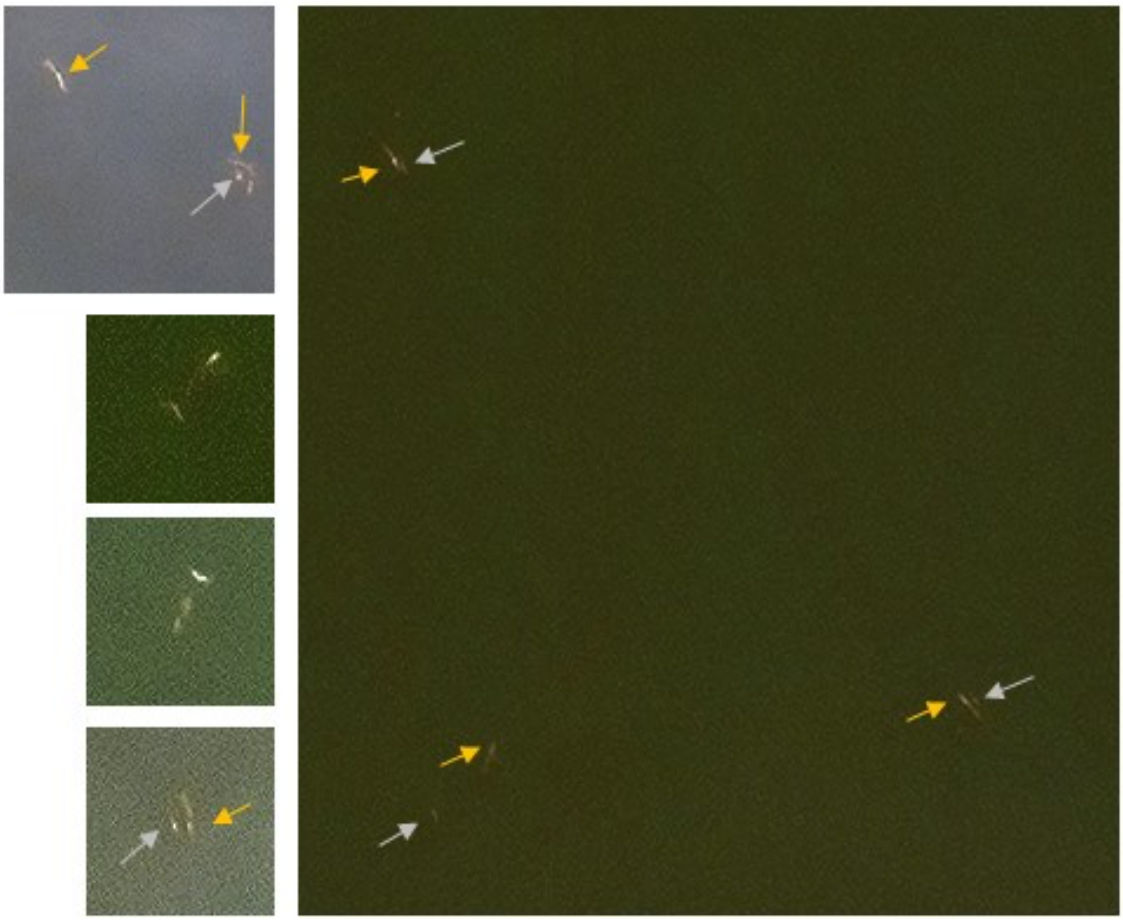

Figure 2). Calves could be distinguished from adult animals from their size and often their proximity to an adult. The distribution of the detections on the two satellite surveys are shown in Figure 3. Of the definite and likely whales, 34% of the whales detected were classified as calves (by the manual ID team) on the first satellite pass (17th August); just 10% of whales were calves during the second pass (25th August). The two passes provided at least some coverage of different areas, with the first covering well known southern right whale habitat of Port Ross, whilst the second pass covered an area south of Enderby Island (also a well-known habitat for southern right whales) but also Ewing Island (Figure 1). Detections south of Ewing Island were largely classified as possible whales. This region is more exposed than the rest of Port Ross and therefore the sea surface conditions in this image were relatively poor and gave rise to false positives. Opportunistic sightings data suggest it is not well used by the whales in comparison to the rest of the harbour (pers. comm. Emma Carroll).

The satellite pass took place one day (17th August 2020) after a team -surveyed the northern part of Port Ross by boat on the 16th August 2020 (Figure 3). While the satellite image is a snapshot the boat survey recorded whales

between 8:50 and 17:33 local time. The numbers of whales within comparable areas for both survey methods were comparable (Table 2).

Table 1 *Overview of southern right whale detections in WorldView-2 satellite images from the 17th August 2020 and 25th August 2020*

Southern right whales	**17 Aug 2020**		**25 Aug 2020**		**Total**
Confidence	**Adult**	**Calf**	**Adult**	**Calf**	
Definite	74	46	5	0	125
Likely	39	12	12	2	65
Possible	35	3	87	2	127
Definite + likely	**113**	**58**	**17**	**2**	**190**
All	**148**	**61**	**104**	**4**	**317**

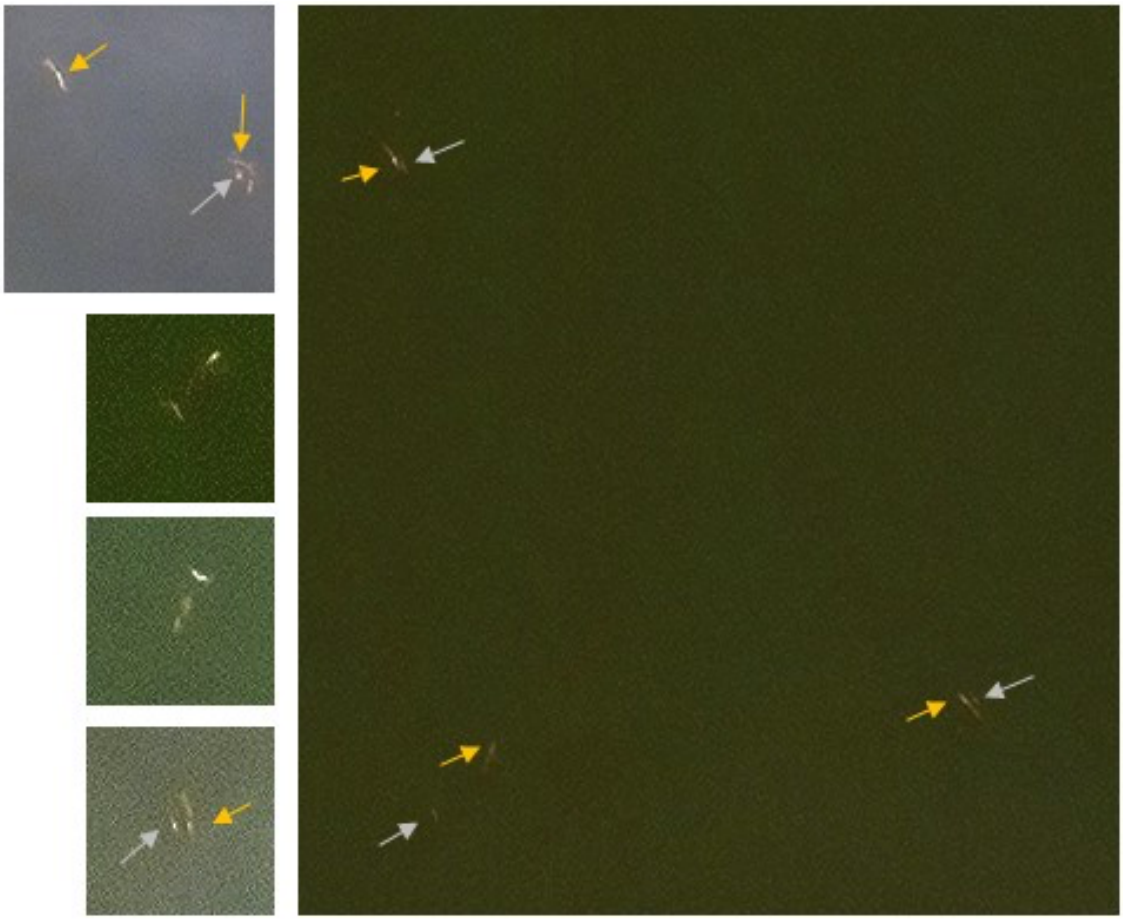

Figure 2 *Examples of southern right whales detected in WorldView-2 satellite image with adults (yellow arrows) and juvenile (grey arrows) (Satellite imagery © 2021 Maxar Technologies) at the Auckland Islands, New Zealand.*

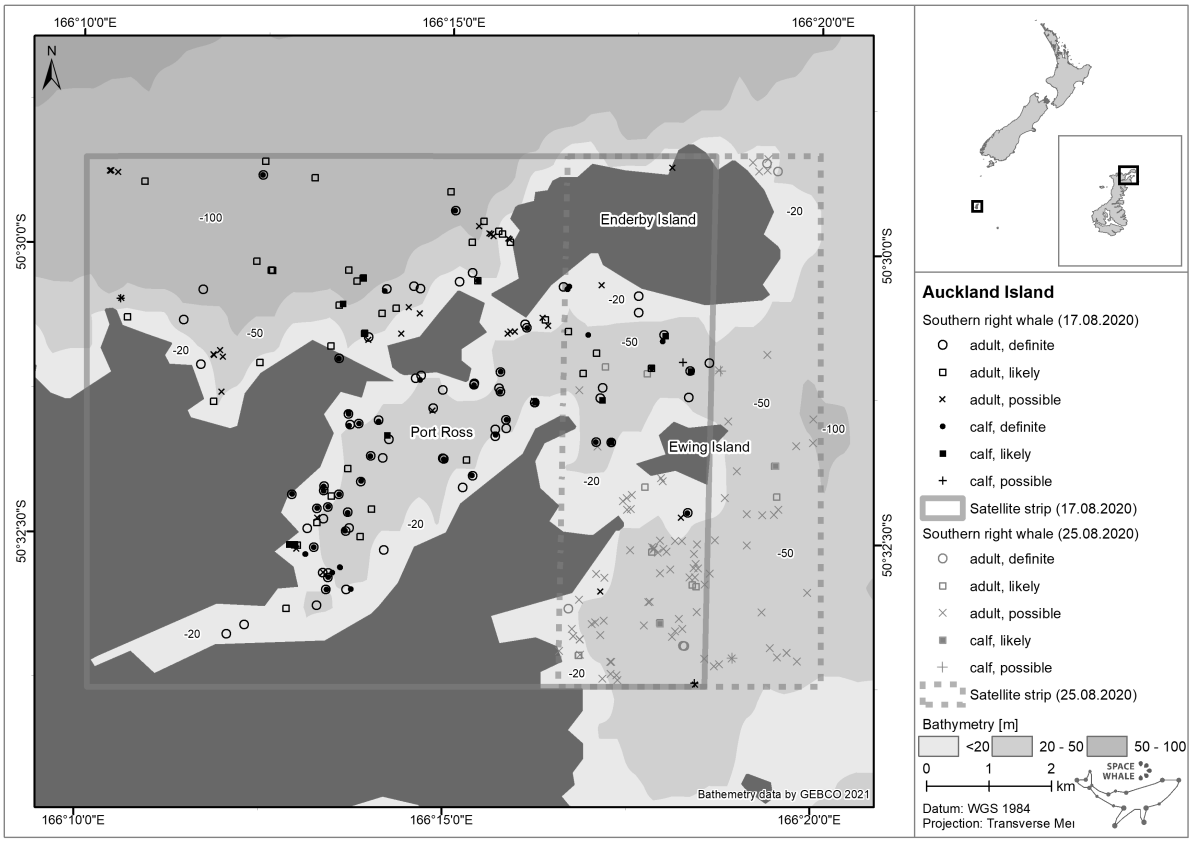

Figure 3 *Distribution of southern right whales from the satellite at the Auckland Islands, New Zealand, for 17th August 2020 (black hollow and filled symbols) and 25th August 2020 (grey hollow and filled symbols) divided into adult and juvenile animal for all confidence levels definite, likely and possible. Possible whales in the satellite strip on 25th August 2020 south of Ewing Island are considered unlikely to be whales.*

Table 2 *Comparison of southern right whale sightings at the Auckland Islands, New Zealand, with the WordView-2 satellite (17th August 2020) and boat-based survey (16th August 2020).*

16 – 17 August 2020	**Number of animals**		
Counts of Southern right whales	**Adult**	**Calf**	**Total**
Satellite survey (Definite + Likely)	25	16	41
Boat based survey	23	18	41

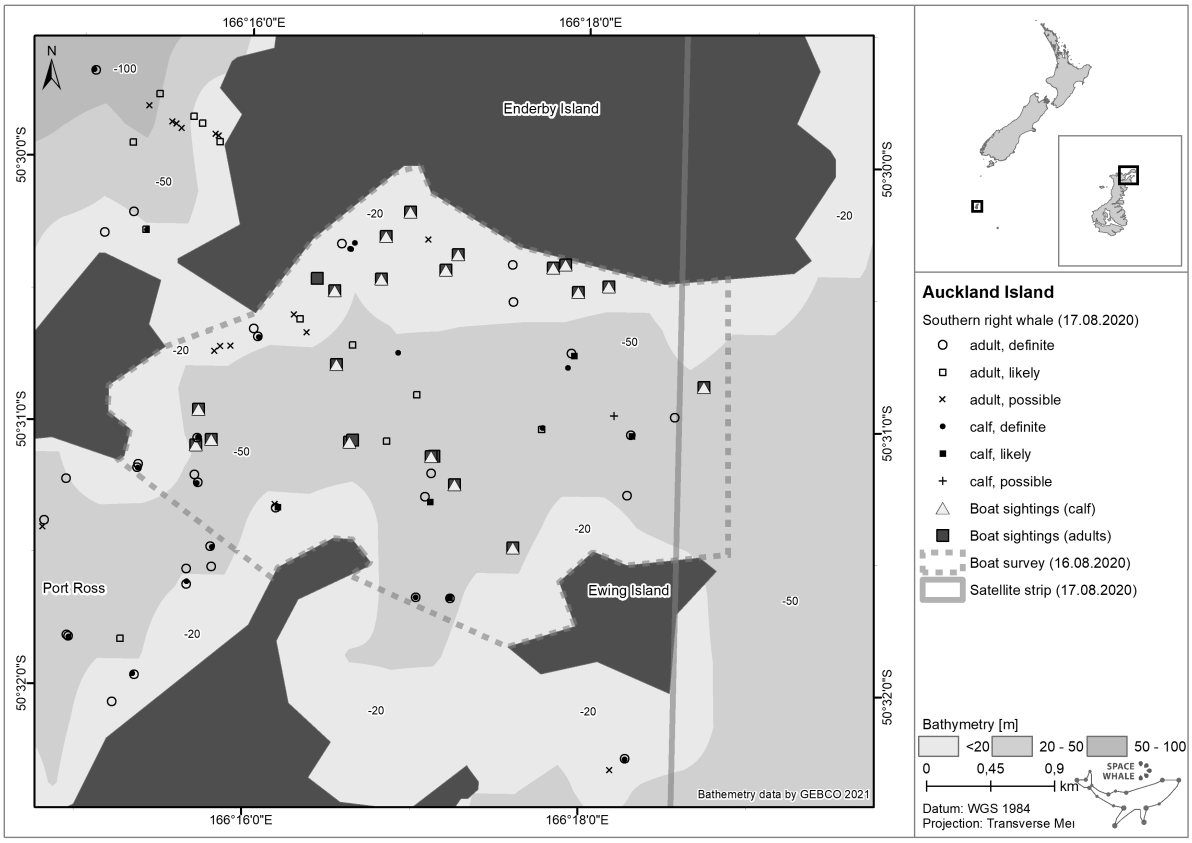

Figure 4 *Comparison of sightings distribution of southern right whales at the Auckland Islands, New Zealand on the 16th and 17th August 2020 for adults and calves from the boat and SPACEWHALE surveys respectively.*

DISCUSSION

SPACEWHALE successfully detected southern right whales in Port Ross using a satellite sensor resolution of 0.46m. Initial attempts to get imagery of a wider area were unsuccessful due to other higher priority taskings of the satellite operator and high cloud cover. However, retrieval of archival, localised images on the wind sheltered area of Port Ross proved successful. Images in this area still had a degree of cloud cover (haze) but SPACEWHALE was still able to detect potential whales. Sea state can also make whale detection challenging, but it was low in the images obtained, owing to the relatively sheltered Port Ross area. The surveys successfully detected 209 potential whales (120 definite and 51 likely) on the 17th August 2020 and 108 potential whales (5 definite and 14 likely) on the 25th August 2020. The highest count of definite whales was 120 (adults and calves) in the larger satellite image taken on the 17th August and this represents a minimum estimate for satellite detections. It is likely that at least some additional whales marked as likely/possible were in fact whales and estimates of the number of whales were also not corrected for those that were too deep and therefore not visible in the images (availability bias); both factors result in negative bias in the counts of whales detected. SPACEWHALE can detect whales submerged in the top few metres of water but water clarity variation in Port Ross will constrain this, as some areas such as Laurie Harbour have high tannin content and low visibility regardless of weather conditions. Further work that makes use of multispectral diversity is ongoing to improve whale "visibility" to the SPACEWHALE algorithm and will contribute to development of an availability bias correction for satellite surveys. For southern right whales in this region, data from the deployment of suitable tags to monitor surfacing behaviour could also provide relevant data to make availability corrections.

The counts of whales from the SPACEWHALE survey and boat-based survey were comparable; coincidentally there were the same number of whales detected by each method. The estimated residency time for cows with calves in Port Ross is 31 days (FEWSTER & PATENAUDE 2009) and high numbers of cow-calf pairs use Port Ross from June to August (PATENAUDE 2001, CARROLL et al. In Review SC/68D/ForInfo/25). We would therefore expect the number of whales to be comparable in the short time span between the boat and satellite surveys. Boat-based surveys did detect more calves which is to be expected given the brevity of the SPACEWHALE survey and the fact that any nursing calves below their mother, or calves lying on top of their mother will be challenging to

detect. Future monitoring with a resolution of 0.30m may help to address detection of calves that are not entirely obscured by their mother's body. It proved to be generally feasible to discern adults and calves, although for reasons already mentioned, it is possible that the number of calves was underestimated. Calves accounted for 38% of all definite whales in the first satellite pass of Port Ross. Recent boat and drone surveys show that, on average, 50% of groups in the Auckland Islands contain cow-calf pairs (CARROLL et al. In Review, SC/68D/ForInfo/25), although the proportion increases across the season and peaks in August (55%-75% of groups, based on data from August 2020, CARROLL et al. in Review, SC/68D/ForInfo/25). Parturient southern right whales prefer calving areas close to the coast (within 200m), shallow (<20m) and sheltered from westerly prevailing winds (RAYMENT et al. 2012, 2014).

Port Ross is an ideal location for southern right whale breeding but there are many other areas along the east coast of Auckland Island that also appear to have similar habitat characteristics and as the species continues to recover (CARROLL et al. 2013) the whales may move into other areas beyond Port Ross (RAYMENT et al. 2012). However, surveys around the archipelago have not found any evidence of aggregations outside Port Ross in the Auckland Islands. The second satellite pass that covered an area beyond Port Ross and south of Enderby Island resulted in many possible whales. The reviewers struggled to provide more definite whale identification in this area as the satellite image exhibited surface reflections of the sun that obscured characteristic features of the whales. Rayment et al. (2012) reported occasional whales in the area outside Port Ross and a dedicated survey with experienced observers (CARROLL unpublished data) reported only a few whales in this region.

Much of the area surveyed in this pass has a comparable depth profile to Port Ross but it is less sheltered, has faster tidal flow and extensive kelp beds. It is unlikely that many of the possible whale detections in this area were whales and further work will be undertaken to see if improvements can be made to reduce false positives e.g., by incorporating drone footage of southern right whales into the SPACEWHALE training dataset. This image was of much lower quality than that covering Port Ross and the issues reported here demonstrate the need for good survey conditions (as with traditional methods) to minimise uncertainty around whale identification.

This study adds to the growing literature that demonstrates satellite surveys can contribute to assessing whale distribution and habitat use by different demographic classes but focuses particularly on a remote and inaccessible area. This approach could also be used to identify additional habitats that may not have received any or much survey effort (e.g., potential breeding and feeding grounds). As Port Ross was declared as an International Union for Conservation of Nature (IUCN) Important Marine Mammal Area (IMMA) in 2020 (TETLEY et al. 2022), satellite surveys can provide cost effective monitoring of the arrival and numbers of whales, and a division of non-calving males and females and mother-calf pairs (CARROLL ET AL. in Review). In the case of southern right whales, males and females, and females with calves, have different probabilities of visiting wintering grounds based on age and reproductive status (CARROLL et al. 2013), and once on wintering grounds, have different residency times (FEWSTER & PATENAUDE 2009) and detection probabilities (data presented here). Such heterogeneity is found in other baleen whale species (e.g., DAWBIN 1997), meaning the use of satellite imagery to estimate total population abundance would require considerable effort to account for individual heterogeneity. However, if the Auckland Islands was surveyed at the same time of year to avoid documented changes in demographic composition of wintering southern right whales over the season (PATENAUDE 2002, CARROLL et al. In Review), a time series of numbers of cow-calf pairs could be generated that could be representative of the reproductive output of the population. As with other wintering grounds, calf production could be linked to environmental variables (e.g., AGRELO et al. 2021) to understand factors influencing population dynamics. Satellites could potentially simultaneously survey both Campbell and Auckland Islands, currently logistically unfeasible during the austral winter for boat-based research.

Furthermore, this approach has the potential to collect open ocean data outside of EEZs that serve relevant baseline information for IUCN IMMAs (TETLEY et al. 2022), International Whaling Commission sanctuaries, and other high-seas management areas. The method could also be applied to look at historical grounds for an indication of whale presence. Satellite surveys offer a cost efficient and safe platform for areas of interest that are considerable distance from land. In 2022, there will be increased capacity to conduct satellite surveys with the WorldView Legion (from MAXAR) and Pleiades Néo (from AIRBUS) satellite constellations being launched. The heightened number of satellites orbiting the Earth means there is greater opportunity to increase the number of passes of an area of interest for the development of long-term monitoring programmes. As the value of evidence from satellite surveys becomes more prominent it will be important that those using the platforms work as a community to maximise data sharing and acquisition across projects to minimise competition for the available satellites. Collectively, information from satellite surveys can make an invaluable contribution to the conservation and management efforts of cetaceans.

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